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Enhancing Facilities Management and Structural Design through Building Information Modeling

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A MAJOR QUALIFYING PROJECT
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Enhancing Facilities Management and Structural Design through Building Information Modeling

Submitted to the Faculty
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Degree of Bachelor of Science
in Civil Engineering by

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Abstract

The project explored using Building Information Modeling (BIM) as a tool to provide continuity in the flow of information from the design/construction phases of the new Center to its occupation/operation by the WPI Department of Facilities. Three structural steel alternatives were designed, presented visually, and then compared to the precast arches located above the natatorium. A decision matrix was used to evaluate the structural options and select the best system based on cost, schedule, maintenance, aesthetics and constructability. A BIM-prototype was created to demonstrate the capabilities of BIM for storage and retrieval of closeout documents and other critical information for the Department of Facilities. This system demonstrates the benefits of using information technology for facilitating the phases of construction and facilities management.

Authorship

All aspects of this project were equally worked on by the four members on the team with a few exceptions. The following chapters were completed by the person below.

3.1 BIM and Facilities Management – James Ricci

3.2 Structural Analysis – Trevor Bertin and Kelsey McMenamy

3.3 Prototype – Peter Schembri

4.0 BIM and Facilities Management – James Ricci and Peter Schembri

5.0 Structural Alternatives – Trevor Bertin and Kelsey McMenamy

6.0 Conclusions and Recommendations – Kelsey McMenamy and James Ricci

The signatures below indicate acceptance of the above.

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Capstone Design

The capstone design of the Major Qualifying Project consists of three main components. First is the analysis of the capabilities of BIM software and the investigation of its uses in facilities management. In parallel with this first component, an example of these capabilities was developed using a mechanical equipment room as a prototype application. Finally three alternative structural designs were developed to replace the precast concrete arches that support the ceiling in the natatorium with steel trusses.

In order to complete the capstone design requirements for this Major Qualifying Project, the team conducted a limited exploration of how BIM software can be implemented into the design and the post-construction phases of WPI's new Sports and Recreation Center. Activities in the disciplines of construction management, structural engineering, and facilities management were used to investigate a number of tasks within the context of BIM. By exploring and implementing various aspects of BIM, our team sought to provide insight into the potential benefits and limitations of BIM to the engineering and facilities management industry. The completed work provided an alternative steel design, and a BIM prototype of a mechanical room. The realistic constraints associated with this project are economic, health and safety, sustainability, social, and manufacturabilty/constructability.

Economic:

Comparing the current precast concrete arch design to the alternative steel truss design involved a cost analysis. The lump sum price of raw materials and fabrication costs, on-site preparation and erection all affect the cost of the project. Implication of one contract for the structural steel alone opposed to the two contracts for the structural steel and the precast concrete of the current design was also considered.

Health and Safety:

Important factors in any project are the health and safety implications presented. The alternative steel designs were prepared in accordance with *The 7th edition of the Massachusetts State Building Code* as well as the *AISC Steel Manual Design Specifications*. Two additional health and safety factors presented when evaluating the steel alternatives were fire protection and corrosion resistance.

Sustainability:

Due to WPI's commitment to have all future construction be environmentally friendly, sustainability and environmental concerns were a major consideration for this project. Through BIM technology, processes used by the Department of Facilities will potentially be enhanced, ultimately enriching the lifecycle of the building. This was achieved through the introduction of the BIM prototype enriched with component specific materials which facilitates the process of storing and accessing data.

Manufacturability/Constructability:

From a manufacturing and constructability standpoint, this project explored the feasibility of using steel trusses as an alternative to the current precast concrete arches. The alternative designs using steel consist of investigating the advantages and disadvantages of steel compared to precast concrete, determining the design loads that the design will support, selecting the appropriate dimensions for the members, and performing a structural analysis on the design. The procurement and erection of manufacturable steel structures also involved consideration of economics and safety because the requirement of a suitable crane to lift the steel members/trusses. If the current cranes on site do not meet these requirements then the cost of an appropriate and additional crane will become a factor.

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Chapter 1 – Introduction

The construction industry is a vital part of the economy of the United States, accounting for over 8 percent of the nation’s gross domestic product. (Bogdan, 2000) The success of any construction project requires extensive communication among owners, architects, engineers, project managers and contractors. While each of the parties’ duties varies greatly, an understanding of all aspects of the project is crucial for delivering a quality project on time and within budget. Throughout all phases of a project, failures in communication result in errors, unexpected and costly changes, delays in the schedule, and loss of vital information for the operation and maintenance of the completed building. With the application of newly developed technologies these difficulties could be averted. Currently the construction industry finds itself in the middle of a technology revolution with the introduction of Building Information Modeling (BIM) technology, but like any addition to any well-established industry, BIM requires time in order to become a standard.

Building Information Modeling is a technological approach to storing and conveying coordinated, consistent, and computable information about the design and construction of a building, with the ability to visually display building components in a three-dimensional view. (Mendez, 2006) BIM’s capabilities are enhanced by a parametric modeling engine, which “…interrelates building objects to other objects and coordinates the changes between them”. (Rundell, 2005) This feature facilitates design decision-making, production of quality construction documents, prevention of structural conflicts, and prediction of cost estimates and construction schedules. While BIM is primarily defined as a modeling method, one of its intrinsic values is to provide a communication bridge within and across the architectural, engineering, and construction communities. By adopting the use of BIM throughout the duration of a project, the overall construction can be completed faster with fewer delays, cost much less to the owner, and ensure effective storage and retrieval of accurate operation and maintenance information for the Owner. (Mendez, 2006)

Currently, Worcester Polytechnic Institute (WPI) is constructing a new Sports and Recreation Center to meet its demand for a growing athletic community.   The new 145,000-square foot Center provides a four-court, 29,000 square-foot gymnasium, a natatorium with a 25-meter competition swimming pool, an 11,000 square-foot fitness space, a three-lane indoor jogging track, as well as robot pits, rowing tanks, convertible racquetball and squash courts, dance studios, and offices for Department of Physical Education, Recreation & Athletics personnel. (WPI, 2010b) With the new Sports and Recreation Center projected to open in the fall of 2012, all students, faculty, and staff will enjoy a facility that allows them to reach their highest athletic potential.

In order to fully ensure functionality of the built environment and deliver a project that meets all of the Owner's specifications, WPI has asked the Construction Manager, Gilbane Construction, to implement BIM within the development of the new Center. While the implementation of BIM prior to the construction phase is usually the most desired, the use of BIM during any phase of construction is beneficial to the project. (Autodesk, 2010) Currently, coordination meetings are held for the mechanical, electrical, and plumbing (MEP) areas. These meetings demonstrate the advantage of BIM in showing the clashes that exist between the trades in three-dimensions.

This report explores the application of BIM from the preconstruction to the post-construction phases of a building project. Investigations were made on how and to what degree BIM can make a difference in these phases to the Owner. In addition to the current practice of using BIM for its visual aid in coordination meetings during the construction phase, our project explores its uses in the design of the project and the operations and management (O&M) storage of building information to the Owner.

By exploring case studies, interviews, and attending the new Center's MEP coordination meetings the potential benefits of BIM for WPI's Department of Facilities were discovered. As a result of our efforts, our team created goals which include: developing a BIM prototype of a mechanical room that display the potential for information storage to support operation and maintenance, a 3D model of an alternative design for the precast/pre-stressed arches spanning the natatorium, and an analysis of the possible effects of the alternative design on the construction schedule and cost.

A substantial amount of background research was conducted as a critical preliminary step to understanding BIM and its capabilities regarding WPI and the new Center. This research, accompanied by an evaluation of the construction materials used in the project, steel and concrete, is presented in Chapter 2. Chapter 3 documents and justifies the processes and the resources utilized to accomplish our goals. Chapters 4 through 6 review our findings for each area of the project scope: BIM in Facilities Management, the design and evaluation of Structural Alternatives, and BIM Prototypes. Chapter 6 provides recommendations for an alternative design and for implementing BIM in future construction projects. As a capstone design and independent learning experience, the project team incorporated previous coursework and field experience to address the possibilities of designing alternatives and incorporating BIM technology into WPI's new Center. It is the hope of the team that this report can be used as a guideline for introducing BIM into all phases of the buildings life-cycle from design to operation and maintenance.

Chapter 2 – Background

This chapter of the report involves the non-technical information about the new Center that will help the project team gain a better, overall understanding of its design and construction planning as well as information on facilities management and its potential capabilities with BIM. The planning and development of a project is key before conducting a technical review. Without this process, unforeseen problems could arise that would be costly to address and would delay the project. The chapter begins with an investigation of the new Center and its various components. Additionally, the chapter covers existing and alternative structural components used in the new Center. Lastly, BIM and related software is discussed along with its relation to Facilities Management

2.1 New WPI Sports and Recreation Center

Worcester Polytechnic Institute, founded in 1865, provides education to 3,453 undergraduate students and 1,153 graduate students, and brings employment to 365 faculty members. (WPI, 2010c) All members of the WPI community are encouraged to use the recreation facilities on campus, and currently there are two athletic facilities available to the entire WPI community.

Alumni Gymnasium, built in 1916, houses offices for faculty, locker rooms, a swimming pool, racquetball courts, and a 4,000 square foot fitness center. Harrington Auditorium, built in 1968, includes a 2,800 seat gymnasium used for sporting events, concerts and a small area for aerobic exercises. These two gymnasiums support 15 Varsity sports teams, 20 club sports, 10 intramural sports, and over 20 physical education classes. With the faculty and student body progressively increasing in size, as well as the student participation in sports, the need for a larger sports facility has become a priority.

The original Master Plan for the new Sports and Recreation Center on the WPI campus was created in 2005. However, further planning and construction was delayed until the Spring of 2009 when Cannon Construction was brought on board as the designer of the project. Due to the economic crisis in 2008, it was realized that 2009 was not a viable starting point, and construction was again deferred. On October 30, 2009, the WPI Board of Trustees agreed to proceed with the construction of the Center starting in May, just after the 2010 Commencement. Project financing currently involves a combination of fundraising, donations, debt, and use of accumulated operating surpluses. (WPI, 2010a) The 145,000 square-foot Sports and Recreation Center is currently under construction at the west end of the campus quadrangle, adjacent to Alumni Field and Harrington Auditorium. A view of the facility from the quadrangle is rendered in Figure 1. A 16-person indoor rowing tank will be located on the ground level of the Center, along with a natatorium featuring a 25-meter competition swimming pool, a training and rehabilitation suite, and specialized spaces for racquetball and squash. This level, shown in Figure 2, will be directly accessible from Alumni

Figure 1: New Center from the WPI Quadn (WPI, 2010b)

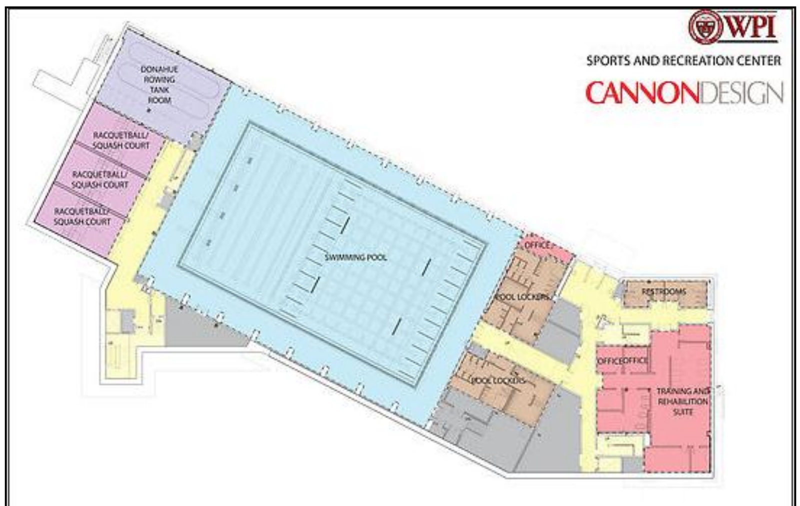

Figure 2: Ground Floor Plan (WPI, 2010b)

field. (WPI, 2010b) The Center will provide space and equipment for activities which currently have little or no designated areas in the existing gymnasiums, such as rowing and robotics.

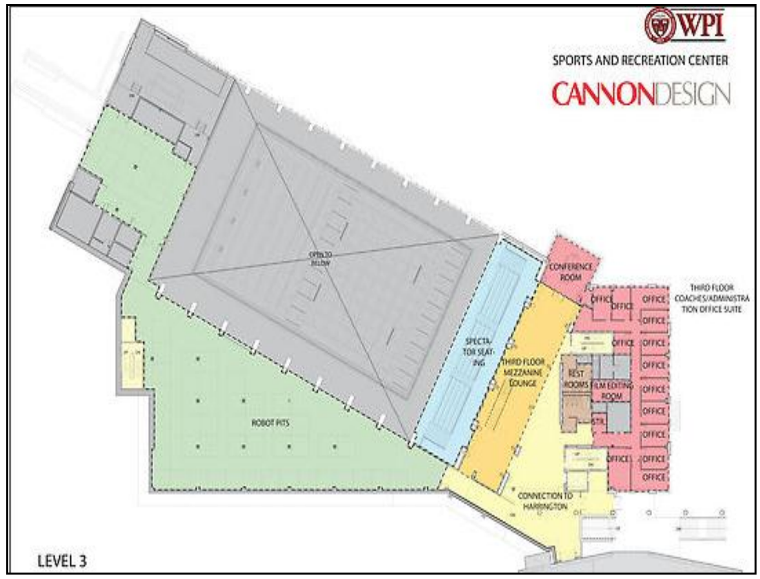

Figure 3: Level Three Floor Plan (WPI, 2010b)

As a technology-based school, WPI holds several robotics competitions for their students and external organizations. Currently these competitions are held in Harrington Auditorium, yet there is limited space for the competitors to test, repair, and program their robots prior to competition. The new Recreation Center will house a robot pit on the 3rd floor that will connect directly to Harrington Auditorium for competitions. The 3rd floor, shown in Figure 3, will also contain spectator seating for the swimming pool, a conference room, and multiple offices for the Department of Athletics' administrators and coaches. (WPI, 2010b)

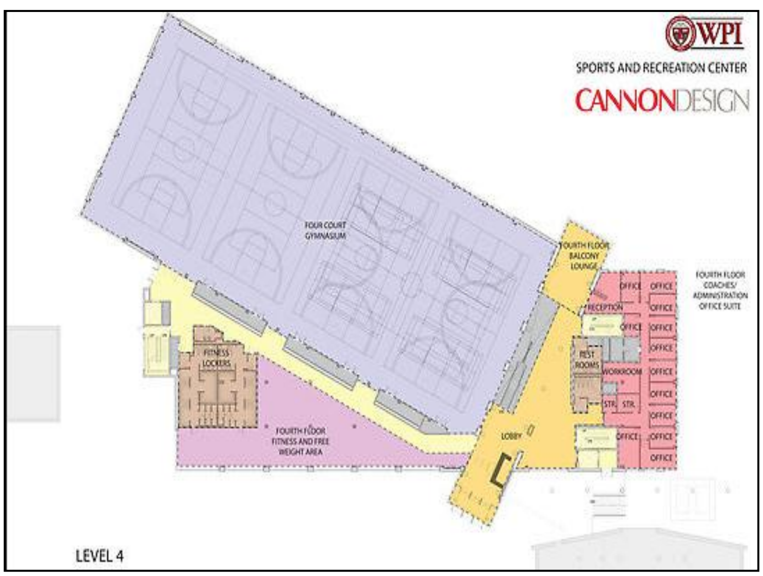

Figure 4: Level Four Floor Plan (WPI, 2010b)

The Center will be accessible from the campus quadrangle at the 4th floor, shown in Figure 4. This level contains 12 more offices, a 29,000 square-foot gymnasium with four courts, locker rooms, and a fitness center. The fitness center expands to the 5th level, supplying a total of 14,000 square feet of fitness space, more than tripling the current size of the fitness area in Alumni Gymnasium. The 5th floor also contains meeting rooms, three multi-purpose rooms, and a suspended jogging track overlooking the gymnasium. Since the new Recreation Center will house activities that currently take place in Alumni Gymnasium, including wrestling matches, indoor rowing, swimming, weight lifting, and racquetball. Alumni Gym will subsequently be converted for academic use. (WPI, 2010a)

2.2 LEED Certification

The new Center is being constructed with the goal of achieving Silver Leadership in Energy and Environmental Design (LEED) certification. There are currently two LEED-certified buildings on the WPI campus: East Hall and the Bartlett Center. (WPI, 2010c) LEED is a rating system started by the United States Green Building Council (USGBC) which encourages sustainable design, construction, operations and maintenance solutions in buildings and communities. Additionally, it establishes protocols and procedures for owners to maintain during construction and occupancy. (U.S. Green Building Council, 2010)

Table 1: LEED Point System for Schools (U.s. Green Building Council, 2010)

LEED® for Schools

Total Possible Points**	110*
Sustainable Sites	24
Water Efficiency	11
Energy & Atmosphere	33
Materials & Resources	13
Indoor Environmental Quality	19

*Out of a possible 100 points + 10 bonus points

**Certified 40+ points, Silver 50+ points, Gold 60+ points, Platinum 80+ points

Innovation in Design	6
Regional Priority	4

LEED uses a point system to designate different levels of sustainability. Points are grouped into five categories. Table 1 shows the LEED categories and possible point totals for schools. Upon completion of a building that is ready to be inspected, a team of LEED Accredited Professionals will determine the point total based on construction procedures, current equipment, and future building protocol. (U.S. Green Building Council, 2010) The sum of these point totals determines the facility's sustainability level.

The new Center will have to obtain 50+ points out of the five categories to achieve Silver certification. The Sustainable Site category awards points for promoting responsible, innovative and practical site design that are conscious of the flora, fauna and water & air quality. The Water Efficiency category grants points for minimal drinking water consumed in the building. The Energy and Atmosphere category promotes the practices of tracking building energy performance, managing refrigerants and using renewable energy. The Materials and Resources category strives to minimize waste while the building is being built and after its construction. The Indoor Environmental Quality category points are awarded for indoor environmental and air quality control as well as thermal comfort. Bonus points are granted for innovative designs that minimize local environmental concerns. (U.S. Green Building Council, 2010) (Mendez, 2006)

In order to achieve the Silver LEED certification, the Center will utilize 50 solar thermal panels on the roof in order to help heat the pool area. Compared to conventional pool heating, the solar panels are expected to save more than $50,000 in operating costs annually and reduce carbon dioxide emissions by 4,400 pounds per year. The Center will also contain underground storage tanks that will collect 50,000 gallons of rainwater from the roof, ultimately reducing the building's water consumption by more than 800,000 gallons per year. Also, more than 75% of the construction waste will be recycled and diverted from landfills. (WPI, 2010a)

2.3 Project Organization

There are many parties involved with design and construction of the Recreation Center. A flow chart of the main parties involved (excluding WPI personnel) is displayed in Figure 5. Assuming the role of Construction Manager for the new Center is Gilbane Inc. Based out of Providence, Rhode Island, Gilbane Inc. is one of the largest privately family-owned companies in the construction and real estate industry. Founded in 1873, Gilbane has taken part in many notable projects, including the Smithsonian

Institute National Air and Space Museum, the Vietnam and World War II Memorials, and the Winter Olympic Venues in Lake Placid, NY. Gilbane has also undertaken many projects that are close to home, such as WPI's Bartlett Center and East Residence Hall. Staffing Gilbane's work force for the project are William Kearney (Project Executive), Neil Benner (Project Manager), Bill Atkins (BIM Modeler), Justin Gonsalves and Melissa Hinton (Project Engineers) and Frank Danahey (Field Supervisor).

Cannon Design, established in 1945, is the design firm for the new Center. They have undertaken the design of the project and submitted the final plans to WPI. Heading the project for Cannon during the construction process is the Contract Administrator, Dominic Vecchione. Mr. Vecchione manages the design process as well as addresses any alterations to the design throughout the construction process.

The Owner's Project Manager (OPM) for the new Center is Cardinal Construction. WPI has a long history with Cardinal on various projects, such as the Life Science Building, East Residence Hall and Goddard Hall, and once again turned to Cardinal for their services. On staff for Cardinal are Brent Arthaud and Michael Andrews as the leading Owner's Project Managers. The role of an OPM is to lighten the load of the owner, enabling them to attend to their everyday responsibilities throughout the construction process. An OPM also provides services including financial and constructability insight. Figure 6 shows the hierarchy of the WPI representatives involved in the project. A flow chart of the main parties involved is displayed in Figure 5, which shows the external organizations (Gilbane, Cannon, and Cardinal).

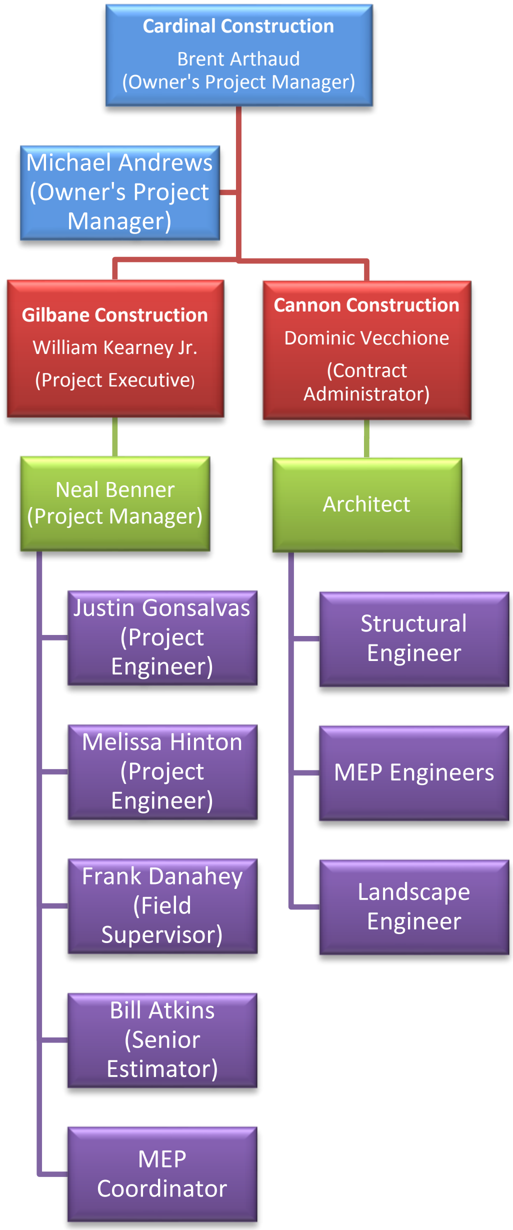

Figure 5: External Organization Flowchart

2.4 Natatorium Structural Alternatives

The two principle structural materials that were used in the new Center, steel and concrete are discussed in this section. Each material has significant advantages and disadvantages. Of particular interest are the precast concrete arches and double-tee beams spanning the natatorium. These arches and double-tee beams represent the only precast concrete used in the building. If these bents were to be replaced steel girders or trusses could be a competitive alternative.

2.4.1 Current Layout

The new Center's natatorium is on the bottom floor; supporting the three floors above the natatorium are nine bents or arches spaced 19'-6" apart from each other and a maximum of 24'-0" away from the closest internal wall. A rendering of the arches over the pool area is shown in Figure 6. Each arch is made out of four pre-cast concrete pieces and one pre-cast, pre-stressed component. They rise 31'-2" high leaving 27'-9" between the soffit at mid-span of the arch and the pool deck. On either end of each bent there is a circular cut out with a diameter of five feet six inches to allow for MEP equipment to span the natatorium. The bents span in the North-South direction. Atop the arches is the floor system for the gymnasium. The floor framing is made out of pre-cast, pre-stressed concrete double-tee beams distributed about 5'-6" apart. They stand 2'-4" high and support a 6" reinforced concrete slab, acting as the floor deck to the gymnasium above. The floor system acts as a diaphragm to gather the lateral forces acting on the building while the bents only support vertical loads. (Cannon Design, 2010b)

Figure 6: Precast/Pre-stressed Arches in Natatorium (WPI, 2010b)

2.4.2 Concrete

The new Center has precast/pre-stressed concrete arches and double tee beams spanning over the natatorium. Precast/Pre-stressed construction is useful because of its improved constructability over cast-in-place construction and its resistance to wear, along with many other attributes. Precast concrete is poured and cured into a specific shape at an offsite location prior to installation. Concrete is placed into forms, made typically of wood or steel, and left to set for 12 to 24 hours after which it is removed. These pieces are then shipped to the construction site and erected. Precast components are reinforced with either reinforcing bars, high tensile strength steel strands, or both. The strands are pre-tensioned and secured in the forms before concrete is placed. After the concrete cures, the strands are cut creating a compressive force applied to the concrete. This is known as pre-stressed concrete. Pre-stressing overcomes concretes tensile weakness allowing increased load carrying capacity over longer spans than ordinary reinforced concrete construction. The advantages and disadvantages of precast and pre-stressed concrete are discussed in Tables 2 and 3. (Anonymous, 2010; Graduck, 1970)

Table 2: Pre-Stressed Concrete Characteristics

Pre-Stressed Concrete – In General			
Advantages		Disadvantages	
Properties	*Description*	*Properties*	*Description*
Reinforced	-Same as conventional reinforced concrete	**Cost**	-More expensive then reinforced concrete
Cracks	-No cracks at working loads -Wires/bars create compression before loading	**Design**	-More complicated
Durability	-With removal of cracks it becomes better than reinforced in durability -Allows use of high tensile steel		
Efficient	-Smaller members carry same loads		

Table 3: Precast Concrete Characteristics

Precast Concrete – In General			
Advantages		Disadvantages	
Properties	*Description*	*Properties*	*Description*
Maintenance	-Doesn't require upkeep	Heavy	-Require large cranes to lift -Can be put together in smaller pieces
Fireproofing	-Has high degree of fire resistance -Non combustible	Corrosion	-Reinforcement bars susceptible to corrosion, iron must be coated
Quality Control	-Easy to produce concrete that meets requirements -High quality because of controlled conditions in factory	Complicated Design	-Difficult connections -Small Margin of error -Limited design flexibility
Durability	-Can be designed for different exposures -Designed against weathering action, chemical attack and abrasion	Elasticity	-Design assumptions are rather indefinite
Cost	-Competitive with steel in cost	Crack	-Weak crack resistance, cracks at working loads -Increases corrosion on reinforcement and concrete -Low tensile strength
Constructability	-Rapid speed of erection -Can be erected year round -Whole building can be precast		
Compression	-High compression strength		
Aesthetics	-Flexible, can be a variety of textures, colors, finishes, and insert options -Plastic, can mimic other materials		
Design	-Flexible: long-span capabilities -Open interiors		
Energy Efficient	-High thermal mass -Insulation		

2.4.3 Steel

The structural frame of the new Center is being primarily constructed out of structural steel. Structural steel is a versatile material that can be used in many situations. Steel is very reasonable when its great strength, light weight, ease of fabrication, and many other desirable properties are considered. The advantages and disadvantages of steel are represented in Table 4. (Eustache, 2006; Durham, 2008; McCormac, 2008)

Table 4: Steel Characteristics

Steel-In General			
Advantages		Disadvantages	
Properties	*Description*	*Properties*	*Description*
Cost	-Low cost per square foot	Durability	-Less durable than concrete with natural disasters and equipment
Design Flexibility	-Spans over 100 ft are not uncommon; makes remodeling easy -Few columns necessary	Corrosion	-Susceptible to corrosion when freely exposed to air and water -Must be painted frequently to prevent corrosion
High Strength	-High strength of steel per unit weight	Fireproofing Costs	-Strength reduced tremendously at temperatures commonly reached in fires -Excellent heat conductor -Need to be protected by materials with insulating characteristics & sprinkler systems
Uniformity	-Properties of steel do not change significantly over time	Susceptibility to Buckling	-As length and slenderness increase of a compression member, danger of buckling increases
Elasticity	-Steel behaves close to design assumptions	Fatigue	-Strength reduced when steel is subjected to stress reversals or variations of tensile stress
Permanence	-Steel frames properly maintained will last indefinitely	Brittle Fracture	-Steel may lose ductility and become brittle at high stress concentrations
Ductility	-Can withstand extensive deformation without failure under high tensile strength -Prevents premature failures -Visual evidence of impending failure		
Toughness	-High yield strength -Can be loaded and deformed without affecting overall integrity		
Constructability	-Fastened together by simple connections -Fast erection		
Reuse/Recycle	-Material can be reused after disassembly -Has scrap value		

Similar to the concrete arches discussed in the previous section, steel has the ability to span great distances unsupported. The simplest way to span a long distance with steel is to use a beam. Typically a W shaped steel beam or I-beam would be used for this purpose. However, to span a distance as long as the existing concrete bents used in the natatorium, a large and heavy beam or a truss would be required. The new Center consists of a 29,000 square foot gymnasium where the ceiling above spans more than 100 feet with no vertical support. Cannon Design used a truss to support the above ceiling and roof. Trusses are a popular and economical structural element used to span great distances. A truss is a framework of structural members consisting of top and bottom chords and diagonal web members. (Integrated Publishing, 2010)

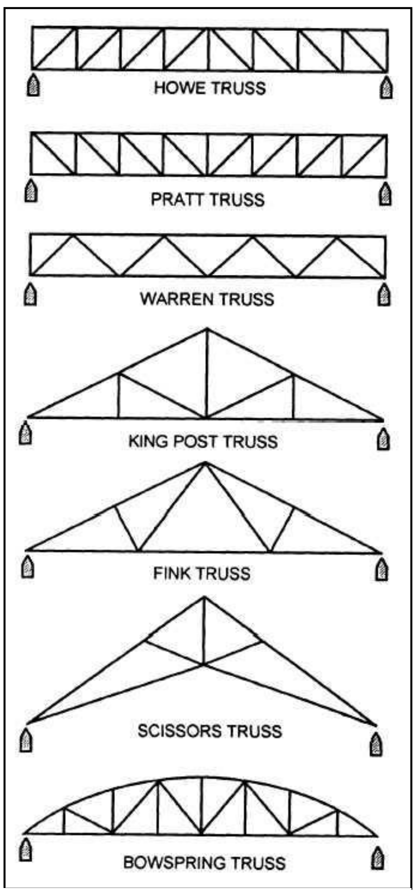

Figure 8: Common Roof Truss Systems (Integrated Publishing, 2010)

Trusses can be fabricated to conform to diverse shapes and sizes which make them versatile construction elements. Many different shaped trusses exist and are utilized depending on the application and the surrounding components. Steel trusses are used for many applications, including bridges, floor systems, and most commonly, roof systems. Figure 7 shows seven popular truss types used for roof systems.

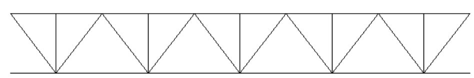

Figure 7: Truss Design Used in New Center

The roof system implemented in the new Center consists of twenty five trusses similar to that of the Warren Truss. This truss system, shown in Figure 8, will be located above the gymnasium floor. Perpendicular to the trusses is a set of cross-bracing elements which resemble another truss. These cross-braces consist of top chords, bottom chords, and web members where necessary. Trusses can be used when MEP systems, such as ducts and pipes, are included in the roof system. There is little volume used in a truss and therefore equipment can run along a ceiling, through a truss, with little or no interference. The versatility of a truss makes it an easy alternative to any roof or ceiling system, especially in the case of the new Center where steel is a main component of the buildings structure.

2.4.4 Design and Evaluation Criteria for Potential Alternatives

In order to implement a truss or I-beam frame system as an alternative design to the precast concrete arches in the natatorium of the Center, several aspects had to be considered. The design criteria included:

1. Design Loads – The first step in designing an alternative was analyzing the loads acting on the alternative and answering the following questions: What was the alternative supporting? Were there vertical and lateral loads? How were the loads found or calculated? This type of information was found in the structural drawings provided by Cannon Design, the designer of the project. The designed alternatives had to meet all codes and requirements.
2. Building Codes – The *Massachusetts State Building Code(MSBC)* was consulted, to determine standard load criteria which were not stated in the drawings or project specifications; and to verify the loads stated in the contract documents. The designed alternatives had to meet all codes and requirements. The MSBC provisions include building safety, fire prevention, and energy efficiency codes.
3. Constraints – There were physical limitations posed by the unique conditions of the Center that had to be noted while designing the alternative. These are outlined below.
    a. Size of the alternative – The alternative couldn't exceed a certain size/depth, which had to match the size of the concrete arches.

b. MEP equipment and other interferences – Similar to the arches, the alternate design had to accommodate the MEP equipment which runs along the ceiling.

c. Connections – There were many different types of connections that had to be considered while constructing the alternatives in the natatorium. The key questions were: How would the alternatives be supported? How would the alternative systems interact with the existing structure opposed to the precast arches? How were the members of the alternatives joined?

d. Corrosion resistance – By replacing concrete with steel in the natatorium, the structural system would become more susceptible to corrosion. A coating application which is aesthetically pleasing and leaves room for fire proofing had to be considered.

e. Cost – In order to design a practical alternative the cost of the alternative had to be competitive with that of the precast concrete. Additional cost had to be considered for fireproofing and corrosion resisting materials.

4. Safety Conditions – As mentioned above, the alternatives had to be fireproofed for safety reasons. This could be a challenge to design since the truss will also require corrosion resistance.

5. Building Layout – The layout of the building played a large part in determining the size of the alternatives and the necessary cross-bracing. This involved addressing the following questions: How far did the alternatives span? Was cross bracing necessary?

Once an alternative was designed using the above criteria, it was evaluated to ensure that the alternative was adequate and practical in the application for which it was used. The alternative was also compared with the original design to determine which approach was preferred. The following criteria were considered to evaluate the alternative designs. A comparison of three alternative steel structures is presented in Table 5.

1. Cost – Did the alternative increase/decrease the cost of the overall project? Were there long term costs associated with maintenance and insurance policies?
2. Schedule – How did the alternative affect the overall schedule of the project? Since the majority of the Center was constructed of steel it was assumed that steel was accessible for purchase and delivery to the site. Did the alternatives need pre fabrication? Would this affect lead time?
3. Maintenance – Does the alternative require more maintenance by the Owner?
4. Aesthetics – If the alternative was to be exposed, how would it look? Would it look unpleasing or out of place? BIM technology was used to visualize the expected appearance of the preferred alternative.
5. Constructability – How did the erection of the alternative system differ of that of the precast arches? Would additional equipment be necessary? Could the alternatives be easily erected? Would there be storage on site large enough to accommodate prefabricated steel members?

Table 5: Steel Alternative Comparison

Steel Alternative Analysis	
Free Standing I-Beam Frame	-Consists of vertical steel columns and a horizontal I-beam -Only takes vertical loads -Supports floor system -Most common building system in construction -Because of large span (110 feet) large and heavy beam required
Free Standing Planar Truss	-Consists of vertical steel columns and a horizontal truss -Composed of triangles -Supports floor system -Only takes vertical loads -Used to span long distances with smaller and lighter members than an I-Beam -Takes up more space than I-Beam -Many connections -Harder to fire and corrosion proof
Rigid Planar Truss	-Similar properties as free standing planar truss except for: -Consists of horizontal truss attached to structural steel frame -Takes vertical and horizontal loads

2.4.5 Cost and Schedule

The existing new Center has two contracts for the building superstructure, one for steel and one for the pre-stressed concrete. If an alternative steel design were implemented for the precast/pre-stressed concrete arches and double tee beams over the pool area then only one contract would be necessary. One contract would have the potential of reducing the cost of the project as well as simplifying its schedule and construction. For instance, the steel arrived on October 19th and the erection of the precast arches began on November 1st. The erection of the steel had to be stopped so the precast arches could be placed. A larger crane had to be used to lift the heavy concrete pieces as well as adding to the cost. This proved to be a very complicated time of the construction phase where much communication was needed as well as strict safety measures. Any clashes between the two contractor's schedules could have resulted in delays. However with one contract for steel fabrication and erection there wouldn't have been this coordination problem, potentially saving time and money.

2.4.6 Visual Integration of Structural Design

When providing structural or design alternatives to the Owner, it is important that the Owner is aware of the effects the alternatives will have on the appearance of the structure. Although cost may be the most significant criteria for choosing an alternative, aesthetics are a close second. In the case where exposed structural elements, the precast arches, would be replaced, a visual representation of all options may be required by the Owner. Renderings created using computer software, such as Autodesk Revit, are widely used as a visual aid of these alternatives for the Owner. These renderings not only allow people without a construction background to visualize the aesthetics of each alternative, but also clash-coordinate other elements to prevent interferences with each alternative. An emerging modeling technology that provides these capabilities in the field of construction is building information modeling.

2.5 Building Information Modeling

Building Information Modeling (BIM) is a relatively new approach focused on the development, use, and transfer of a digital information model of a construction project to improve the design, construction, and operations of a building and its facilities. BIM provides a digital representation of a building as an integrated database of information incorporated within the model of a structure. (Eastman, 2008) A BIM model takes all of the information that is usually found in separate trade-specific Autodesk Revit files and integrates them into an all-encompassing master database.

When properly implemented on any construction project, BIM has proven to provide many benefits which facilitate the construction phases. The value of BIM has been illustrated through a number of case studies, where well-planned projects yield: increased quality of design with BIM's 3D visualization capabilities, improved craft efficiency by visualizing each trades' work in coordination meetings, and decreased interference between components with clash detection; and many more. (Khemlani, 2004) At the conclusion of a project, valuable information can be used by a Facilities' Department for asset management and maintenance scheduling to improve the overall performance of the facility.

2.5.1 Autodesk Revit Systems

The Revit platform is Autodesk's purpose-built solution for building information modeling. Applications such as Revit® Structure, Revit® Architecture, and Revit® MEP built within the Revit platform are well-coordinated, discipline-specific designs for the construction of any project. Typically during the design phase, the project evolves from the Owner's purpose of constructing the building to a multitude of 2D-plans and 3D building views created through the Revit software family. In the case of the WPI Sports and Recreation Center, Cannon Design created the initial architectural, structural, and MEP designs in the respective Revit software. At the heart of every Revit application are the 3D visualization features and the Revit parametric change engine. With parametric modeling, the building design is always kept up-to-date, because the Revit platform automatically coordinates changes made anywhere in the file – in 3D model views or 2D drawing sheets. Discipline-specific design teams (architectural, structural, MEP, etc.) use their own Revit application to create their part of the building design. At strategic checkpoints during the design process, these discipline-specific design models are shared to create an integrated project model. Without the use of the Revit platform and its applications, major system designs, generated by each scope, are not linked through the parametric modeling engine and therefore are incapable of interacting with each other. The inability of these designs to interact with the rest of the structure results in using the traditional 2D-coordination process, thus negating the benefits of using clash coordination.

A product that delivers this review software for the coordination of each Revit design on a project is Autodesk Navisworks – a program which "takes a complex building information model and allows the user to collaborate, coordinate, and communicate more effectively to reduce problems during the design and construction phase." (Autodesk, 2007) While coordination of these Revit files should ideally start at the beginning of the design process, with the architect and engineers working in a 3D environment, the Sports and Recreation Center at WPI has implemented Navisworks' clash detection feature through the initial stages of the project's construction phase. Even though visualization is the number one use of BIM, trade coordination is currently offering the most "bang for the buck" in today's market (BIM Forum, 2009). Early coordination between trades in the design process allows the design team to visualize the relationships between each construction element and avoid clashing elements with that of other trades.

2.5.2 Autodesk Design Review

"Studies suggest that the number of people needing to consume versus create design information is about 10 to 1 – DWF was created for [these] consumers." (Autodesk, 2007) Autodesk Design Review software helps design teams view, markup, print, and track changes to building information models. DWF files are "published" designs – they are not the original design model and they can't be edited; only marked up.

DWF files can carry very large data sets in a very compressed format – a gigabyte-sized building information Revit file can be compressed to a DWF file that's small enough to email. (Autodesk, 2007) The ability to publish to DWF files is embedded in all Autodesk Revit applications, which allows users to publish their design data – multipage drawing sets and the 3D model – in a single print-ready file. Design Review software "reads" the DWF file format and allows the viewer access to the rich set of building information design data while still retaining an explorable 3D model.

DWF files are not building information models; instead they are a mechanism for publishing information from the Revit building information model and sharing that information with extended teams. (Autodesk, 2007) Design Review allows users, such facilities managers, to publish and share information with non-Revit users in order for the recipient or client to visualize the design. The DWF Viewer provides powerful 3D viewing capabilities allowing users to navigate through saved 3D views that can be rotated, cut by cross-section, and even have the ability to hide desired building components.

The Revit user controls how a building model is published to DWF. For example, a facilities manager could publish a DWF file that contains just the plumbing drawing set and the plumbing model components together with the architectural underlay. Someone viewing this DWF file can measure distances, areas, and angles. For instance, a maintenance contractor could measure the area of a room or the distance located between the plumbing and the wall. Properties associated with building components are also transferred from the Revit building model to the DWF file. In Design Review, the user selects an object – a pipe, for example – and can see all of the properties associated with that object: the pipe diameter, pipe length, required pressures, associated equipment, and so forth.

Using DWF coupled with Autodesk Design Review and Revit modeling software allows users to quickly and easily share that understanding with all the team members in the building process: the architects who are designing the building, the Owner who's paying for the building, the workers on site who actually build the building, and facilities managers who are maintaining the building. Publishing building information models using Revit and the DWF file specification, "is a better and more efficient way to communicate a building design," because the program gets the right information to the right people – accelerating all phases of construction and putting the design information in the hands of the people who need it. (Autodesk, 2007)

2.6 Facilities Management

The mission of the WPI Department of Facilities is "to provide a safe, clean, properly maintained environment for the WPI community," in support of its academic, athletic, and social activities. (Department of Facilities, 2010) The Department of Facilities is responsible for maintaining all the physical components of the buildings owned and operated by WPI. This includes mechanical systems, heating and air conditioning systems, fire suppression and detection systems, emergency/security systems, electrical, plumbing, building envelope and lock systems. The Department's purpose is to "broadly oversee the Institute's physical assets" and more specifically, "to maintain the adequacy and condition of capital assets, to develop and periodically review policies, to advocate for new structures and rehabilitate or remove older structures, and to make certain that adequate levels of funding exist for facilities maintenance and operations." (Department of Facilities, 2010) However, the areas of most concern are the MEP and HVAC systems, as these are more prone to needing routine maintenance. Another item of concern is the consistency of building components. The desirability of a facilities department would include common building components, such as lighting fixtures, among the campus buildings for the purpose of reducing inventory costs and having a consistent system. The Department of Facilities is directed by Alfredo DiMauro and organized into multiple divisions, such as Customer Service Center, Building Projects & Renovations, and custodial and technical trades (See Figure 9).

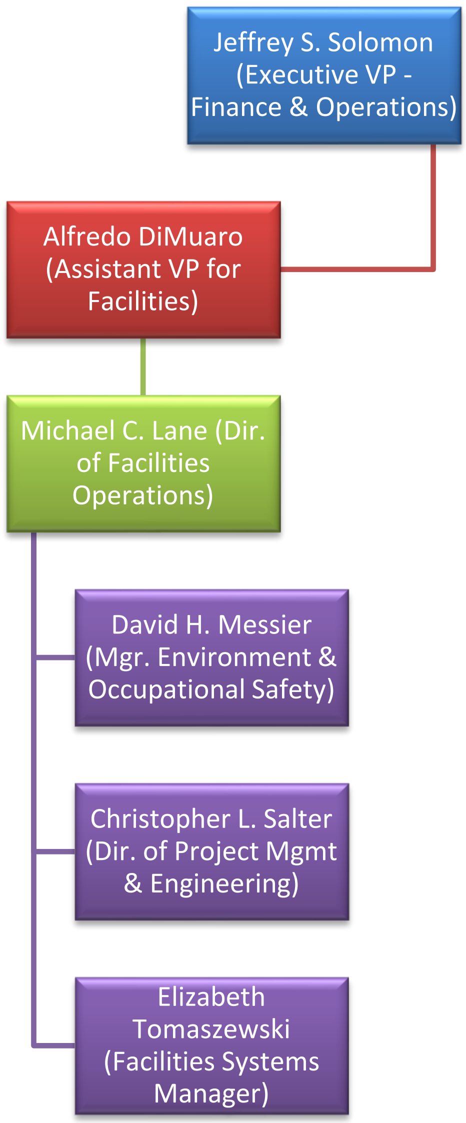

Figure 9: Department of Facilities Organizational Chart

2.6.1 New Center Close-out Documentation

The MEP systems will require much attention during construction as well as post-construction by the WPI Department of Facilities. The complicated systems will need to be maintained properly by WPI in order to run efficiently for years to come. In order to help owners manage their new buildings, closeout documentation is provided at the end of the project to the owner for their reference and future use. A list of the documentation Gilbane must provide to WPI can be found in the Closeout Procedures located in Section 01 1000 of the Project Specifications. The required documentation includes but is not limited to inspections, warranties, final cleaning, operation and maintenance data, and record drawings. Record drawings, also known as "as-builts", are a revised set of drawings created by the contractor or subcontractors which reflect all changes made to the contract drawings throughout the construction process. They show exact dimensions, geometry, and locations of all elements of the work completed under the contract. (Business Dictionary, 2010)

With current 2D as-built drawings, necessary maintenance information about equipment or material is not easily accessible. Necessary information includes operational instructions for equipment, maintenance guidelines, warrantee information, testing schedules, and manufacturer information. Each piece of equipment installed in the new Center will have this information accompanying it, which is important for the operations within facilities management. An example of equipment vital to the lifecycle of the building would be the generator located on the rooftop. Facilities management would need to know not only the information shown in the as-built drawings, but would also need to incorporate the other close-out documentation listed above which is received separately from the as-built drawings.

The incorporation of operations and maintenance (O&M) information and other closeout information in 3-D as-built drawings is a feasible concept, however has yet to be implemented by WPI's

Department of Facilities. Building Information Modeling, or BIM, has made this process possible through its ability to attach attributes to physical components. BIM utilizes computer software to create a three-dimensional (3D) model of a project, which includes the MEP systems, structural and architectural elements, and almost everything in between. It also can store information about each element placed in the model. A further description of BIM's functions and capabilities is described in Sections 2.10 and 2.12.

2.6.2 Building Operations and Maintenance

On a college campus, buildings are intended to provide the students and faculty a healthy, active, and educational environment. In order to make this happen, facilities management is generally concerned with the life cycle of the buildings as well as their energy efficiency so that the interior environments are comfortable and healthy. The life cycle of a building refers to the view of a building over the course of its entire life – in other words, viewing it not just as an operational building, but also taking into account the design, installation, commissioning, operation and decommissioning phases. Energy efficiency is not so easily defined – its issue being that the topic is relatively ambiguous. (Mendez, 2006) According to an M.S. Thesis written by Ronald Mendez, "The perpetual issue for managers has been the cost of supplies and services, and not about standards because no laws setting such limits have been established."

The United States Department of Energy (DOE) states that, addressing operations and maintenance with a predictive maintenance approach will detect the onset of equipment degradation and to address the problems as they are identified. This approach allows casual stressors to be eliminated or controlled prior to any significant deterioration in the physical state of the facility. (U.S. Department of Energy, 2007) Ultimately this method leads to more functional capabilities of a facility. In creating an effective O&M program, the Department of Energy recommends that the following procedures be considered (U.S. Department of Energy, 2007):

- Ensure that up-to-date operational procedures and manuals are available
- Obtain up-to-date documentation on all building systems, including systems drawings
- Implement predictive maintenance programs complete with maintenance schedules and records of all maintenance performed for all building equipment and systems
- Create a well-trained maintenance staff and offer professional development and training opportunities for each staff member
- Implement a monitoring program that tracks and documents building systems performance to identify and diagnose potential problems and track the effectiveness of the O&M program. Include cost and performance tracking in this analysis.

In order to assure the environment that a college campus wishes to provide for its community, a predictive maintenance approach would likely be considered. The DOE's recommendation list, while thorough, provides many obstacles for facilities managers and their staff to accomplish when implementing a program that looks to complete all of these tasks for its buildings.

2.7 Background Summary

The construction industry's traditional resistance to incorporate technological change has prevented benefits from new technologies to grow. Building Information Modeling is a rapidly evolving technology to capture information electronically throughout the phases of a construction project. Worcester Polytechnic Institute's Sports and Recreation Center has utilized this new technology in various construction tasks, one being the coordination between the mechanical, electrical, and plumbing equipment with the structural elements. However implementation of the technology has yet to be employed for the design and post-construction phases of the project. At project completion, WPI receives closeout documentation from the Construction Manager, which consists of information vital to the processes of the Department of Facilities, such as as-built drawings, operation and maintenance manuals, warranties, etc. The intent of this research is to explore how BIM could be used to: visualize an alternative structural design of the precast arches located in the natatorium, and provide continuity in the flow of information to be used by the Department of Facilities at WPI.

3.0 – Methodology

The main goal of this project was to explore the capabilities of Building Information Modeling which would facilitate two phases of a construction project, the design and post-construction processes. The post-construction section of our report focuses on the closeout process between the Owner and the Project Manager and addresses the obstacles faced by the Department of Facilities concerning the operation and maintenance of the completed construction project. The design section of this report focuses on the process between the architect, structural engineer, and Owner and concentrates on the structural aspects of the Center's natatorium to propose an alternative design.

In order to accomplish this goal, the initial priority was to better understand the technology of BIM and determine uses for its capabilities that would facilitate each process. A list of objectives relating to the topics discussed above was created to complete the project. These objectives were:

- Understand important criteria involved in managing a construction project
- Explore BIM technology and its potential capabilities for the post-construction/ Department of Facilities' processes
- Design alternative steel structures to replace the existing structure and floor system for the natatorium
- Create a BIM prototype that demonstrates BIM's information storage for the Department of Facilities and exhibits BIM's visual aid for the design alternative

To accomplish these objectives, current case studies, interviews and methods for structural design based on previous coursework were used. The information derived from these resources was implemented in the creation of two BIM models; a visual model incorporating the chosen alternative steel design, and an HVAC room that services the natatorium for the Department of Facilities.

3.1 BIM & Facilities Management

BIM technology was incorporated throughout the design and construction phases of the new Center. Cannon Design used BIM in the design process to develop the structural and architectural layouts, while Gilbane integrated the technology throughout construction for the 3D design coordination of MEP components, fire protection and the Center's structure. However, there was no intent to explore and integrate the Center's BIM with the closeout building documentation for the post-construction phase. This section of the methodology focuses on the following tasks in order to create a BIM prototype for the Department of Facilities:

- Investigate current closeout procedures and documentation
- Gain familiarity with the Department of Facilities' processes and closeout items vital for their responsibilities
- Research BIM technology and its potential capabilities for the post-construction phase/ Department of Facilities' processes

3.1.1 Investigation of Current Closeout Procedures and Documentation

In order to become thoroughly familiar with the Center's closeout procedures and its closeout documentation, the team built on prior knowledge of the construction phases by researching the Center's Project Specifications and interviewing with member(s) of Gilbane's Project Team. Access to Gilbane's FTP database allowed for examination of the Project Specifications and the contract between WPI and Gilbane for the new Center. The purpose for this investigation was to develop an understanding of Gilbane's closeout procedures and the documents that will be given to WPI after successful completion of the new Center. For example, Section 01 7823 – Operation & Maintenance Data includes the administrative and procedural requirements for preparing the operation and maintenance manuals. Information from this section aided in making the team knowledgeable about the specific requirements and allowed for the development of questions for an interview with Gilbane's Project Engineer, Justin Gonsalves.

The interview with Mr. Gonsalves served to further understand information about the items discussed in the Project Specifications and contract, which are not contained within the documents. The purpose of the interview questions (found in Appendix B) was to gain additional information on these procedures and documents from an experienced Project Engineer in order to determine the duration of the closeout process, establish a timeline on the delivery of O&M material, and comprehend the form in which the closeout material is physically given to WPI.

The combination of knowledge gained from research and interviews provided a strong understanding of the post-construction phase and its materials. This knowledge enabled the development of insightful questions for the facilities management portion of research.

3.1.2 Department of Facilities at WPI

To become thoroughly familiar with the Department of Facilities and their processes, the general background knowledge of the department was enhanced by an interview with WPI's Facilities Systems Manager, Elizabeth Tomaszewski. The interview with Ms. Tomaszewski built on the knowledge gained from investigation of the closeout process, because enquiries about the O&M documents that are handed over to WPI after construction were able to be made. The information of interest uncovered by the interview questions were:

- Distinguish vital closeout documents for the Department's practices
- Determine how the Department currently stores all of the closeout documentation.
- Develop an understanding of the Department's responsibilities and the processes associated with them

The main purpose of the interview questions (found in Appendix B) was to comprehend the Department's practices and identify the O&M information used for these practices, in order to incorporate BIM's potential capabilities for the Department's use.

3.1.3 Research in BIM's Potential Capabilities

Due to limited understanding of this new technology, it was found imperative to research current case studies involving BIM and its benefits, if any, for facilities management. Case studies for this method had to be relevant to either the development of the post-construction phase, or the processes of the Department of Facilities.

As one can imagine the amount of preliminary research on the topic was extensive due to the abundance of resources. This step was found to be necessary because it provided an enhanced understanding of the technology's many capabilities and applications. Once the results from the previous two tasks were received, an application for BIM and its capabilities was investigated to accommodate the post-construction phase and the processes defined by our interview(s) with the Department of Facilities.

Primarily case study research focused on: the implementation of BIM, its information storage capabilities, and the use of complementary software, such as Autodesk Revit and Design Review. Identification of five studies relevant to one or more of the focuses listed above. These case studies were:

- Autodesk Revit: Implementation in Practice
- Revit Building Information Model: BIM & DWF
- BIM Project Execution Planning Guide
- The Building Information Model in Facilities Management

Results from this task were summarized in a chart that documented: the source of the case study (for additional information), what it explored, knowledge of BIM learned through the case study, and how it can facilitate the closeout phase and/or the Department of Facilities' processes. Ultimately, the information gained from investigating the post-construction phase, the Department of Facilities' practices, and the capabilities of BIM technology was applied in the creation of an efficient BIM prototype for the use of the Department of Facilities discussed in Section 3.3.

3.2 Structural Analysis

Three proposed alternatives to the precast arches and one alternative floor system were developed to support the gymnasium above the natatorium. In addition to supporting the gymnasium, the columns of each alternative must also support the columns from the above floors (3rd, 4th, and 5th floors), their connecting structural components, and their associated loads. The structural alternatives are a free standing I-beam frame, a free standing planar truss and a rigid planar truss. The free standing I-beam and planar truss are both portal frames, in one a W-shape spans the natatorium, and a truss spans in the other. The rigid planar truss is supported by the existing column line on the quad side of the natatorium. Truss types and related materials are discussed in Section 2.4 of the Background. The proposed alternatives were designed to hypothetically replace the existing precast bents, precast double-tee beams, and gymnasium floor system above the natatorium. Our team decided to design three separate alternatives in order to provide several options and find the most preferred design. The three designs chosen are practical structural solutions for the conditions and constraints presented in the new Center. Although hypothetical, these designs are meant to be a competitive structural alternative to the arches in the aspects of cost, schedule, constructability, maintenance, and aesthetics.

The existing system and alternatives are evaluated by this criteria and compared to each other to determine the most viable alternative.

3.2.1 Gymnasium Floor System Design

In addition to replacing the precast bents, the floor above the natatorium, supporting the gymnasium, was also redesigned since the current use of precast double T-beams required two contracts and coordination between iron workers, carpenters and laborers. Therefore, alternatives were examined to determine an adequate system of steel beams and concrete slab on metal decking that is comparable to the double T-beam and concrete slab system. The process of this design is presented in Figure 10.

Cannon Design's contract documents, in particular the structural drawings, were used to ensure that the proposed floor system would have similar properties to the floor systems that were defined throughout the building. Some assumptions and measurements used, such as the type of floor system, thickness and strength of the concrete slab, steel decking properties, and the unbraced length of girders, matched those of the existing building.

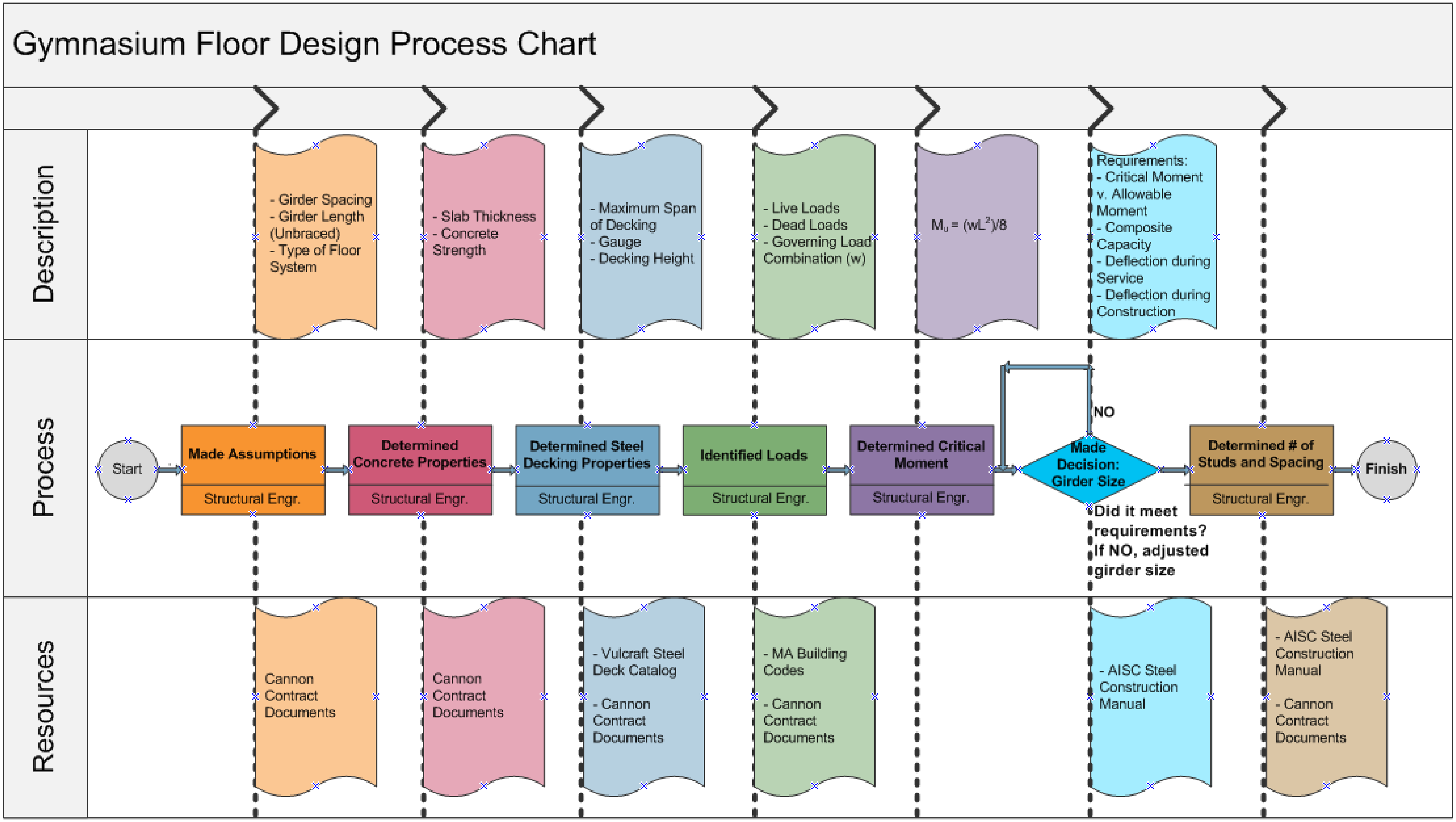

Figure 10: Gymnasium Floor Design Process Chart

3.2.2 Alternative 1 – Free Standing I-Beam Frame

The free-standing portal frame is the simplest concept. The fame consists of two columns supporting a W-shape girder or I-beam. Because of the large span involved the girder will be relatively deep and heavy. Additionally without any penetrations to allow the MEP equipment to run through the I-beam the MEP duct will have to hang below the beam. However, I-beams are of a simple design and easy to coat with protective materials such as fireproofing and corrosion proofing. The frame was only designed for vertical loading because the precast bents are not part of the buildings lateral force resisting system. The process used to develop a design for the free-standing portal frame is presented in Figure 11.

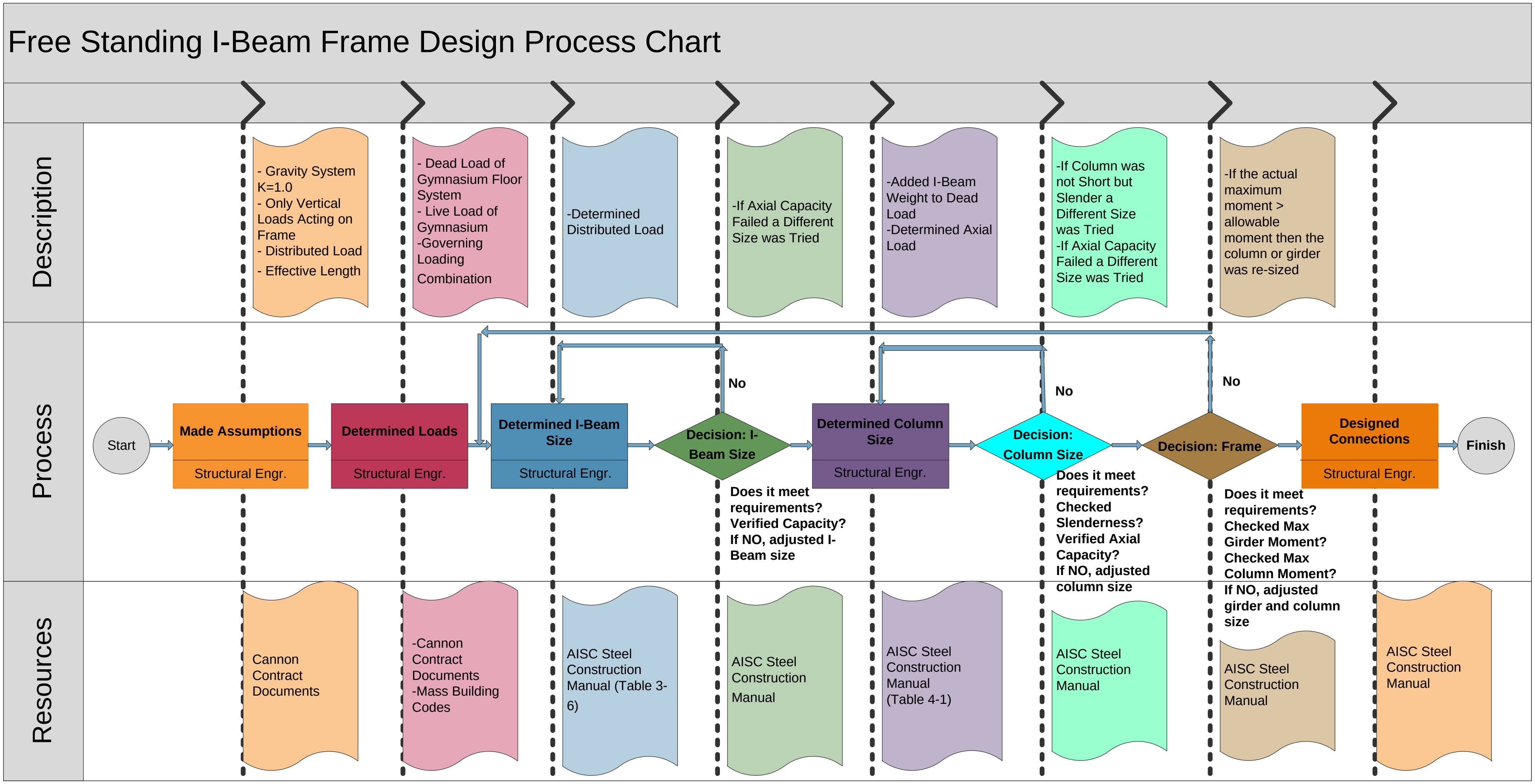

Figure 11: Free Standing I-Beam Frame Design Process Chart

3.2.3 Alternative 2 – Free Standing Planar Truss

The free-standing frame with a horizontal truss was the second alternative developed. This portal frame consists of a planar truss supported by two columns. Unlike the frame, the truss does not have to carry the MEP system below it because trusses have spacing between the web members that can allow for MEP systems to pass through. However trusses are generally much deeper than girders and will impact the clear height between the pool and the truss. Similar to alternative one, this alternative was only designed for vertical loading. The process used to develop a design for the free-standing frame with a horizontal truss is presented in Figure 12.

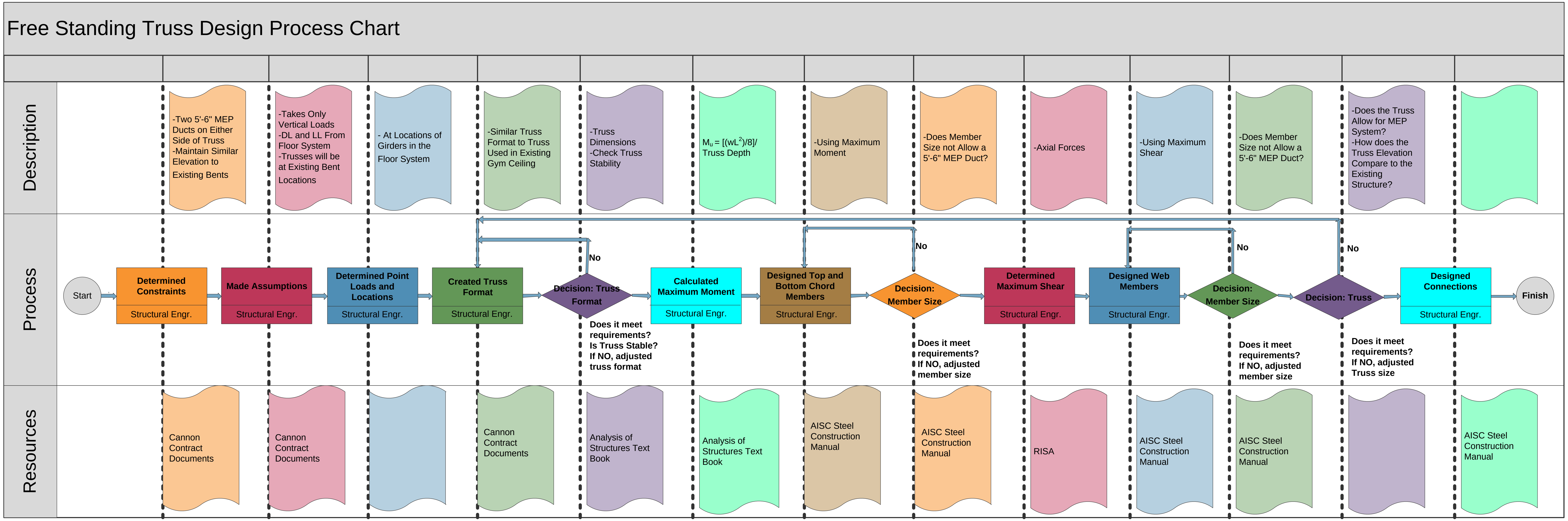

Figure 12: Free Standing Truss Design Process Chart

3.2.4 Alternative 3 – Rigid Planar Truss

The third alternative was also a planar truss. However the horizontal truss was integrated into the existing steel columns of the new Center, shown in Figure 13. This design took both vertical and horizontal loading unlike the previous alternatives. The rigid planar truss also required different connections because it is not free standing. The processes used to develop a design for the rigid truss is similar to that of the free standing planar. However, the capacity of the existing columns had to be evaluated for this new configuration. Additionally the truss had to directly support a column that conveys loads from overlaying floors. The process used to develop a design for the rigid planar truss is presented in Figure 14.

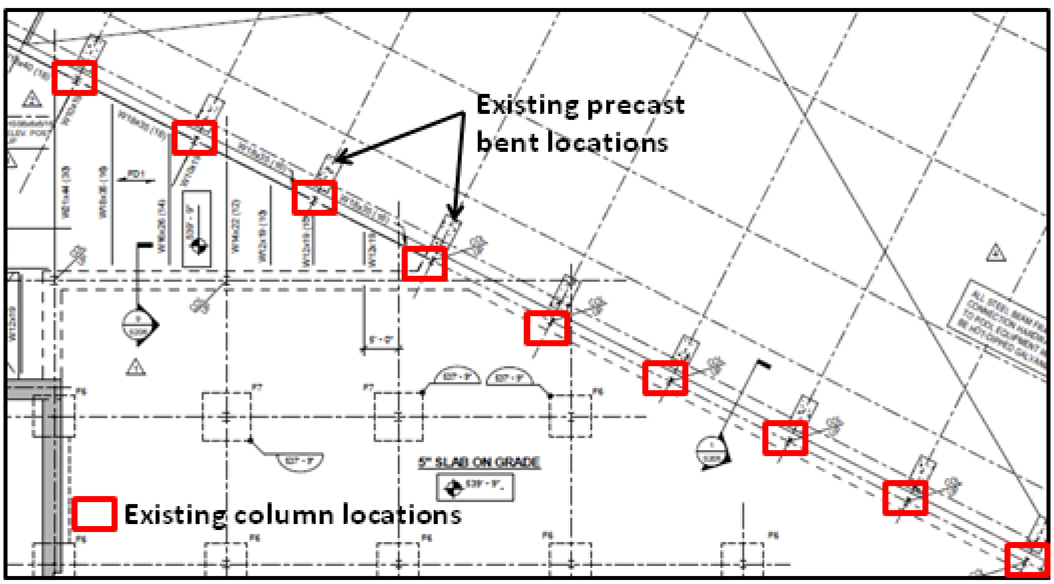

Figure 13: Existing Column Locations for Alt 3 Connections

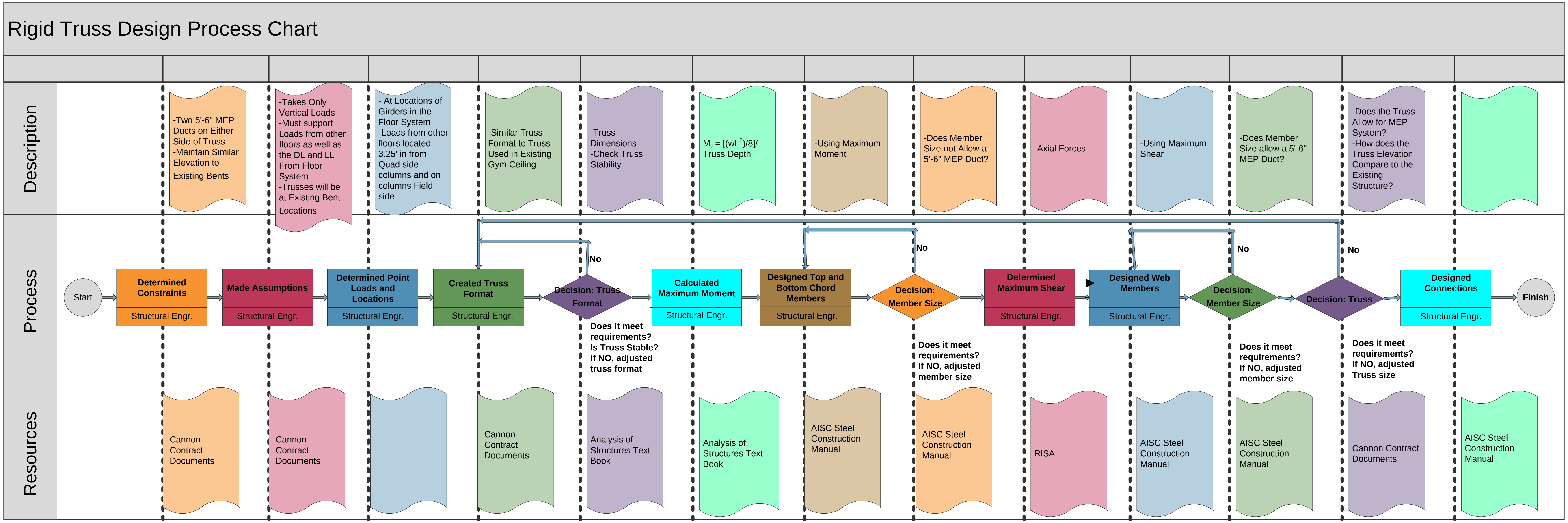

Figure 14: Rigid Truss Design Process Chart

3.2.5 Cost Estimates and Schedule

The cost estimates of the existing system and the alternatives (1, 2, and 3) were calculated using estimates received from Gilbane Construction and RS Means cost data. A total cost of the precast arches and double T-beams, including material, labor, and equipment was provided by Gilbane along with a unit price for steel and general labor costs. The cost was broken down into major factors: material, labor and equipment, shown in Table 6.

Table 6: Cost Analysis Factors

Category	Items Included	Costs
Material	Steel – Raw material, Fabrication, Delivery Concrete – Cast-in-place	$2000/ton $4/CF
Labor	Steel Production Rate	0.134 tons per hour
Equipment	Concrete – 350 Ton Crane Steel – 290 Ton Crane	Both cranes are of similar prices – negligible cost difference
Existing System	Precast/Pre-stressed Concrete, Delivery, Erection, Equipment	$1.5 Million

The unit material price for the structural steel was assumed to be the same unit price that Gilbane paid for steel in the new Center which included: material, fabrication, deliver, equipment, and labor. Using RS Means the percentages for material, labor and equipment were determined for steel and precast concrete. The total cost of material, labor, and equipment was calculated for each alternative and compared to determine the least expensive structural system. A production rate for steel erection was calculated to determine the length of time that would be needed to place and connect the alternatives. Based on these production rates, man-hours were calculated for each alternative and an estimated schedule was developed.

3.2.6 Constraints and Evaluation

Since the alternatives will consist mostly of structural steel members and components rather than concrete and will have a different shape than the arches, a few constraints had to be considered before the alternatives were designed.

- Corrosion – The presence of the pool creates a humid atmosphere in the natatorium. The high humidity and chemical vapors from the pool increase the risk of corrosion. The steel must be covered in a corrosion resisting coating.
- Fireproofing - The steel must also be fireproofed. There may be difficulty in coating the steel in both fireproofing and corrosion-retardant. For a truss alternative it may be hard to fireproof all corners and more maintenance may be required for steel rather than concrete.
- MEP System - The alternative structure must accommodate the current MEP design which is contained in two five foot six inch diameter ducts.
- Size – The alternative structure must be about the same size/depth as the existing bents
- Cost – The alternative must be at a competitive cost

In order to determine a preferred design, certain criteria were used to analyze the three alternatives. These criteria include:

- Cost – Which design is most cost effective in the short term and long term?
- Schedule – Which design is most advantageous to the overall schedule of the project?
- Maintenance – Which design requires the least amount of maintenance by the Owner?
- Aesthetics – Through use of 3D modeling software, which alternative is the most aesthetically pleasing?
- Constructability – Which design is simplest to construct or has the smallest impact on the other trades and operations on site?

All of these constraints were considered during the design process of the alternatives and each was evaluated using a decision matrix with the above evaluation criteria, represented in Section 5.7

3.3 Prototype

To best demonstrate the capabilities of BIM in the design and post construction phases of a project, a prototype BIM model with a corresponding information database was created. This model would demonstrate how the Department of Facilities can exploit this technology for the organization of important operation and maintenance information with a user friendly system. Also a 3D model retrofitting our team's alternative steel designs into the current project model would demonstrate the benefits of utilizing BIM in the design phase of a project. The design processes of these two models are depicted in Figure 15 and Figure 16.

3.3.1 Initial Requirements for Prototype

To begin designing the BIM prototype for use with facilities management, a location for the model first had to be identified. To best display the capabilities of BIM technology and its potential uses for the Department of Facilities a room containing MEP or HVAC equipment was desired. Using a room that contains these components could better demonstrate BIM's potential for storing information used by facilities management. To find a possible location Justin Gonsalves was consulted and project drawings were reviewed. A cluster of MEP rooms on the first floor along with an HVAC room on the third floor were considered to be the best candidates for the model.

The information that would be incorporated into the model then became the next focus. Interviews were held with Elizabeth Tomaszewski to determine what information would be beneficial to have incorporated into the model. This information was later accessed through the use of the Project's File Transfer Protocol (FTP) site and the Closeout documents for the new Center project.

3.3.2 Investigate Revit

With this model being our team's first experience using the Autodesk Revit system, it was essential for time to be taken to familiarize ourselves with the software and its capabilities. Autodesk provides various tutorial materials through the student/education portion of their website. These tutorials were in PDF form and were an exceptional reference to the procedures involved in using the Revit software. Autodesk also has published video tutorials on YouTube, which gave a step by step demonstration of how to perform actions in the software. These videos were also referenced during this learning process.

3.3.3 Creation of the Model

Once the team became more familiar with Autodesk Revit construction of the model was able to commence. The first part of the model that was developed was the Architectural and Structural portions. Dimensions and elevations were taken from Cannon's structural PDF files found on the FTP site. Since no one document displays all the interior dimensions, the information had to be scaled off of the drawings. The primary drawings used were A100 and A302.

Upon completion of the architectural and structural parts of the model the MEP and HVAC equipment then needed to be added. To avoid having to create each component individually the most current coordination models were accessed from Gilbane. From these models the specific components and systems chosen to be included into the prototype were retrieved and inserted into the model.

To adapt this model to meet the needs of the department of facilities, each element in the model had to be edited to display information found to be crucial through the research of the team, described in detail in Section 3.1 - BIM and FM.

3.3.4 Creation of the Database

To store the information tagged to the components in the model a database was developed. Microsoft Publisher software was used to create this portion of the project. The information stored in the database came from the research done by our team which is described in detail in Section 3.1 – BIM and FM. The webpage containing the information required for the prototype was uploaded onto the WPI server to make it accessible to the Department of Facilities, as well as ensure access in the event of a loss of internet. Once the database was completed it was merged with the model. The information stored in the database was tagged as attributes to the various MEP and HVAC components in the model to create the final BIM prototype for the Department of Facilities.

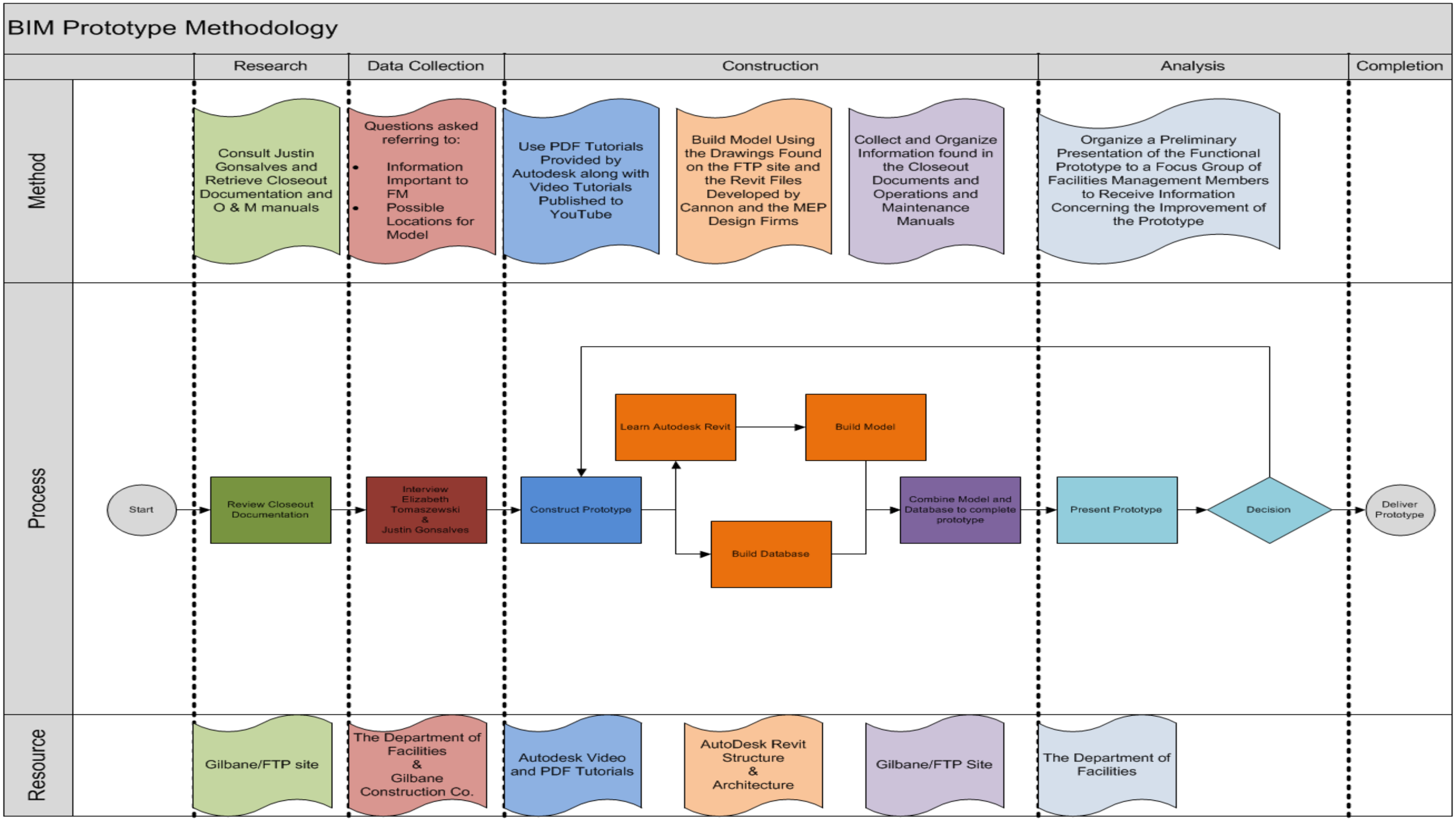

Figure 15: BIM Prototype for Department of Facilities Process Chart

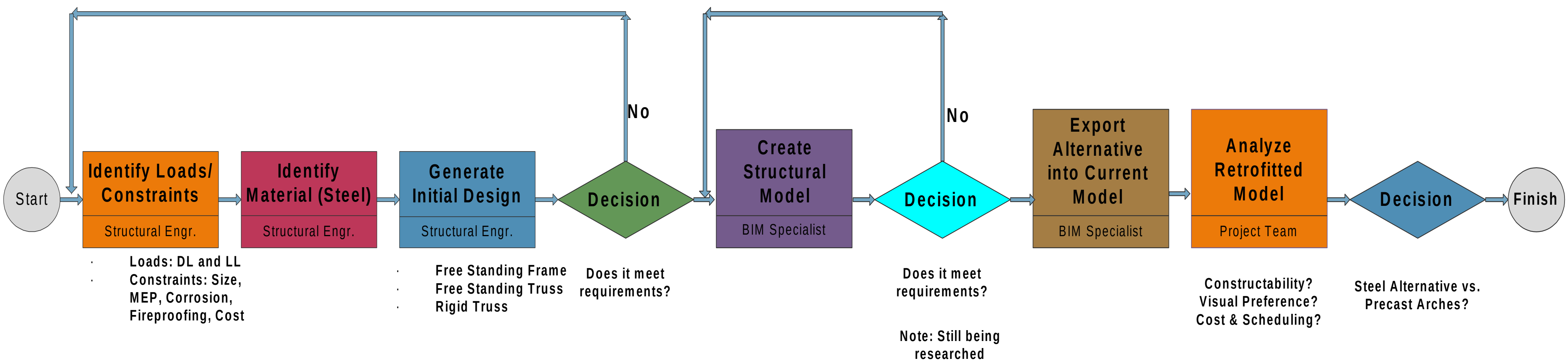

Figure 16: Alternative Design and BIM Implementation Process Chart

4.0 – BIM and Facilities Management

The goals of the BIM prototype were to display and document the capabilities of BIM for use by the Department of Facilities at WPI. In order to accomplish these goals, the following tasks were established:

- Investigate closeout procedures and documentation for the Recreation Center
- Gain familiarity with the Department of Facilities' processes and the closeout items vital for their responsibilities
- Research BIM technology and its potential capabilities for the post-construction phase/ Department of Facilities' processes

These tasks allowed the project team to determine the feasibility of implementing BIM into the closeout phase of construction. Furthermore, if BIM were to be implemented in future construction projects, this chapter also explores how the Owner or Department of Facilities could use the technology coupled with the Operations and Maintenance (O&M) information to facilitate the processes of the Department.

4.1 Investigation of Current Closeout Procedures and Documentation

In this section, the results are discussed from the research of the Center's current closeout procedures and documentation. This involved referencing Gilbane's FTP database to access the Center's Project Specifications and interviewing Mr. Justin Gonsalves, the Project Engineer for Gilbane. The objective was to understand the current closeout procedures and identify places where BIM technology could be implemented throughout or after the construction project. The obstacles associated with adding a new technology to a traditional process were also discussed with the Project Engineer, as well as the feasibility of collecting the closeout documentation.

4.1.1 Project Specifications

Four sections of the Project Specifications were reviewed to gain an understanding of the closeout procedure. These sections were:

- SECTION 01 7700 – Closeout Procedures: includes the procedures and deliverables for contract closeout, inspection procedures, and warranties
- SECTION 01 7823 – Operation and Maintenance Data: includes the procedures for preparing operation and maintenance manuals for all systems, subsystems, and equipment, O&M documentation directory, emergency manuals, and maintenance manuals for the care and maintenance of products, materials, and system equipment
- SECTION 01 7839 – Project Record Documents: includes the procedures and transfer requirements for all of the Project Record Documents, including the Record Drawings, Specifications, and Product Data, as well as any additional content including markups of the Record Prints
- SECTION 01 1000 (1.12) – Transfer of Electronic Files: discusses the preparation, coordination, specifications of electronic files, or Autodesk Revit .rvts, given to WPI by Cannon Design

A summary of the research on the Center's Closeout Procedure can be found in Table 7. The procedures involved for collecting, organizing, printing, and transferring the closeout documents are of particular interest to this report. This process involves the coordination of all parties: the Construction Manager, the Owner, the contractors, and a lot of paperwork. As shown in Table 7, every document pertaining to a system, subsystem, piece of equipment, etc. needs to be printed out and organized into a manual that meets the specifications of Section 01 7700 and Section 01 7823. As a construction project becomes relatively more complex with systems, subsystems, and equipment the more printed documents/manuals the closeout procedure will involve.

Table 7: Required Closeout Procedures for the Center

Contract Section	Description	Topic	Procedure	Details
SECTION 01 7700	Closeout Procedure for Substantial and Final Completion	Substantial Completion	• Prepare a list of items to be completed and corrected (Punchlist) • Submit specific warranties, bonds, maintenance service agreements, final certificates, etc. • Include occupancy permits and operating certificates • Inspection certificates confirming compliance with codes and regulations for: elevators, plumbing and drainage, HVAC, fire protection, and electrical • Submit changeover information related to Owner's occupancy, use security, operation, and maintenance	Organize warranty documents into an orderly sequence based on the table of contents of the Project Manual 1. Bind everything into heavy-duty, 3-ring binders with thickness as necessary to accommodate contents 2. Provide heavy paper dividers for each seperate section. Mark tab to identify product/installation. Provide a typed description of the product/installation, including the name of the product and the name, address, and telephone number of installer. 3. Identify each binder on the front and spine with the typed title, Project name, and name of Contractor 4. Provide additional copies of each binder to include O&M manuals
		Final Completion	• Submit certified punchlist • Submit evidence of final insurance coverage • Submit Project Record Documents, demonstration/training videos, O&M manuals, final completion construction photographs, and surveys	
SECTION 01 7823	Procedure for preparing O&M manuals for all systems, subsystems, and equipment	O&M manuals	• List of all documents, systems, and equipment • Identify each system, subsystem, and piece of equipment with the same designation used in the Contract Documents • Organize each manual into a separate section for each system, subsystem, and piece of equipment • Operation data necessary for: systems, subsystems, equipment, operating standards, operating procedures, operating logs, wiring diagrams, control diagrams, piped system diagrams, precautions, license requirements including inspection/renewal dates, and emergency response procedures	Organize warranty documents into an orderly sequence based on the table of contents of the Project Manual 1. Bind everything into heavy-duty, 3-ring binders with thickness as necessary to accommodate contents 2. Provide heavy paper dividers for each seperate section. Mark tab to identify product/installation. Provide a typed description of the product/installation, including the name of the product and the name, address, and telephone number of installer. 3. Identify each binder on the front and spine with the typed title, Project name, and name of Contractor 4. Provide additional copies of each binder to include O&M manuals
SECTION 01 7839	Preparation/submittal procedures for all Record Drawings and Specifications	Record Prints	• Maintain one set of blue/black-line white prints of the Contract Drawings which show the actual installation of all systems, subsystems, and equipment	Give particular attention to information on concealed elements that would be difficult to identify/measure later. Record data as soon as possible after obtaining it. Record and check the markup before enclosing concealed installations.
			• Content: dimensional changes, revisions, depths of foundations below first floor, locations/depths of underground utilities, revisions to routing of piping/conduits and electrical circuitry, actual equipment locations, duct size and routing, changes made by addendum/change orders, and record information on the Project	Organize Record Prints into manageable sets, binding each set together in a 3-ring binder
		Record CAD Drawings	• Before inspection for Certificate of Substantial Completion, prepare a full set of corrected CAD Drawings	Incorporate changes and additional information
SECTION 01 1000	Transfer of Electronic Files	Specifications	• Canno Design will provide electronic files in AutoCAD 2007 format • Cannon Design makes no representtion regarding the accuracy or completenes of the electronic files • These elecronic files are not Contract Documents, the signed Contract Documents shall govern	

Even someone who is an outsider to the specifics of this closeout process can notice the multitude of information that is transferred to the Owner, and ultimately the Department of Facilities, after final completion of any Project.

4.1.2 Interview with Justin Gonsalves

In order to further inquire about the amount of information transferred, as well as the length of time involved with the closeout procedure, Mr. Justin Gonsalves, Project Engineer for the Center, was consulted for further understanding. An overview of the interview questions is presented in Figure 17, and the complete interview can be found in Appendix B.

Figure 17: Interview Questions on Closeout Process and Documentation

Sports & Recreation Center Closeout Process and Documentation
Interview Questions

How involved is the close out documentation process?
How much time/effort is spent gathering the information?

Are the contents of the contractual agreements standard for the industry or just for WPI?
What kinds of requirements are inconvenient to produce?

What additional items do you think could be provided to the Owner for their benefit at close out?

When asked about the amount of information that is transferred during the closeout process, Mr. Gonsalves responded that the amount of information shown in the Center's Specifications would not be "through the roof ridiculous" and that "the information involved [with the Center] is pretty standard compared to other projects." From an Owner's perspective, Mr. Gonsalves informed that

Owners typically get “overwhelmed with the amount of closeout information” being transferred to them at the conclusion of the project. Looking ahead, a convenient storage and retrieval method for all of this information is essential in order to refer to these important documents for future use.

One idea that arose was a digital library, where closeout documentation can be stored with minimal physical space (typically a computer) and can easily be referenced within the computer’s directory. Additionally, when asked about having one large directory for the closeout documents, Mr. Gonsalves not only thought that the idea was “pretty neat,” but that it would also be fitting, seeing that Gilbane publishes all of the closeout documentation to PDF versions.

Mr. Gonsalves informed that Gilbane Construction begins their closeout process at the start of the project because they’ve realized the difficulties in motivating a Project Team to compile the required documents at the Project’s conclusion. With an early start, collecting, organizing, and finally transferring the multitude of information becomes a gradual updating process which is made easier by the number of staff on the Project during the construction stage. Gilbane further simplifies this “pretty involved process” by requiring all contractors to deliver all of their O&M information upon delivery of all systems and equipment to the site. Although the use of BIM cannot change the process by which the Construction Manager receives closeout documentation, it will suggest a similar gradual updating process of all the systems, equipment, and components.

4.2 Gaining familiarity with the Department of Facilities

Section 4.2 builds on the knowledge gained from Section 4.1 - to suggest the implementation of BIM for storing and accessing the Project’s closeout documents, especially the closeout items that are vital for facilities management. In this section, the results are discussed from an interview with Mrs. Elizabeth Tomaszewski, the Facilities Systems Manager at WPI. As Facilities Systems Manager, Mrs.

Tomaszewski is responsible for many operations throughout campus; one in particular is her responsibility for operating, maintaining, and improving the current work order system (with new approaches) at WPI.

During the interview, Mrs. Tomaszewski was presented with a list of the items received during the closeout procedure from Sections 01 7700 and 7823 of the Project Specifications, and asked their importance. The response was that the "most important [items] for a Facilities Manager are the floor plans with windows, doors, etc…operating procedures, and warranties are definitely needed." The storage of these documents within the Department currently consists of two types of libraries, digital and paper. While cataloguing the digital library is ongoing, everything that the Department has for its facilities is found in the paper library, which is comprised of "huge volumes of drawings, prints, and specifications that are uncategorized."

The Department's work order process is dependent on the resources stored within these libraries: drawings, specifications, O&M manuals, etc. As work orders are generated, the paper library is consulted for the information pertaining to the work order. It is often useful to attach scanned layouts of the room, specifications and warrantee information about the equipment, etc. to the work order, but this process takes time. Mrs. Tomaszewski further stressed that there is a strong hope in the future for the Department to have the ability of connecting digital drawings, warrantees, etc. to these work orders. While the current procedure of physically going through the paper library is not considered to be time efficient, the Department's set back is the resources (time, money, manpower) needed to load and manage this O&M information within their digital library, Creating an easy and efficient link between the digital library of the systems on campus and their O&M information became one focus of the research presented in Section 4.3. The capabilities of a BIM process for this purpose would require a simple reference guide that also links access to an organized digital library of the O&M information for any particular object.

Currently the Department only uses a preventative maintenance approach on its HVAC system, although they would like to implement this approach throughout their operations. Similar to the Department, Mrs. Tomaszewski believes that "if you schedule maintenance you avoid costly downtime and repairs later on." The Department would like to have a new maintenance plan in place by June 2011, at which time they will start with all of the chillers across campus as a prototype and progress from there.

Following the interview with Mrs. Tomaszewski, the requirements for potentially using BIM to facilitate the work order processes and suggest a preventative maintenance approach became more apparent. In order to implement BIM, use of the technology by the Department would require:

- Convenient storage and time-efficient retrieval of large amounts of digital information on the building's systems, equipment, and other elements
- Digital information would need to be uploaded prior to the Department's use
- Organized and user-friendly template for time-efficient reference

By having first established the closeout documents involved in the Center, the importance and uses of these documents by the Department were identified. With these key documents and their associated uses, a framework/strategy was developed researching the capabilities of BIM for facilities management.

4.3 Capabilities of BIM for the Department

In this section, the results are discussed from the research of BIM and its capabilities that pertain to the practices of the Department of Facilities at WPI. This investigation applied the uses of the closeout documents by the Department (found in Section 4.2) and researched capabilities and attributes of BIM that may facilitate the use of this information. White papers, case studies, and a thesis paper were referenced to identify the capabilities of BIM and implementation guidance that would benefit the Department's current work orders and future preventative maintenance practices.

As defined in Table 8, Asset Management is an organized system that, theoretically, will aid in the maintenance and operation of a facility and its assets throughout the lifecycle of a building. It assists in short-term operations, like work orders, and long-term preventative maintenance. *The BIM: Project Execution Planning Guide* defines a record BIM as an accurate representation of the physical conditions and assets of the building. It contains all dimensions and closeout documentation relating to the main architectural elements, MEP systems, and equipment. With a record BIM, the data contained data that will allow the Department of Facilities to:

- Capture and store O&M user manuals and equipment specifications
- Analyze the conditions of the work order and retrieve the relevant information to be used in the work order preparation
- Maintain up-to-date facility and equipment data
- Track the use, performance, and maintenance of a building and its assets
- Produce accurate inventory of the building's assets
- Update the record BIM after upgrades, replacements, and maintenance
- Generate helpful work orders with accurate measurement tools and visualization capabilities

Computerized Maintenance Management Systems (CMMS) and Enterprise Asset Management Systems (EAMS) are two types of software, additional to BIM, that change the management of a building from the traditional retrieval and upkeep of physical paperwork to a self-maintained digital library. The digital library provides easily accessible information for facility-related decisions in a convenient storage space.

Table 8: BIM Case Study Findings Chart

Feature/Finding	Resource	Description	Potential Value	Resources Required	Team Competencies
Asset Management	**BIM: Project Execution Planning Guide** Pennsylvania State University	A process in which an organized management system will efficiently aid in the maintenance and operation of a facility and its assets. These assets, consisting of the physical building, systems, and equipment, must be maintained, operated, and updated at an efficiency that keeps the model up-to-date.	Store and maintain up-to-date facility and equipment data including maintenance schedules,warranties, cost data, upgrades, replacements, damages/deterioration, maintenance records,manufacturer's data, and equipment functionality Provide one comprehensive source for tracking the use, performance, and maintenance of a building's assets for the owner, maintenance team, and financial department Allow for future updates of record model to show current building asset information after upgrades,replacements, or maintenance by tracking changes	Autodesk Revit	Ability to manipulate, navigate, and review a 3D Model and asset management system
Record Modeling	**BIM: Project Execution Planning Guide** Pennsylvania State University	A process used to display accurate representation of the physical conditions and assets of a building. A record model can contain information relating to the main architectural elements and MEP systems. With continuous updating of a record model, it stores all of the building's closeout documents and contains a true depiction of the building and a link to its information.	Provide documentation of building and its systems and equipment for future referencing	Autodesk Revit	Ability to use BIM modeling application for a facility's updates
Preventative Maintenance Scheduling	**BIM: Project Execution Planning Guide** Pennsylvania State University	A process in which the functionality of the building's structure, systems, and equipment are maintained over the operational life of a facility. Theoretically, a successful maintenance program will improve building performance, reduce repairs, and reduce overall maintenance costs.	Plan maintenance activities proactively Track maintenance history Increase productivity of maintenance staff because the physical location of the equipment/system can be clearly communicated	Autodesk Design Review, Building Automation System, Computerized Maintenance Mangement System	Ability to understand and manipulate CMMS and building control systems within Revit Model
DWF Technology	**BIM and DWF** Autodesk	The purpose of this white paper was to explore how DWF technology can be used with BIM as a means to facilitate the sharing of a model's information that comes from a BIM.	DWF files are "published" designs - the Autodesk Design Review software allows users to view, markup, print, and track changes to Revit files. DWF files can carry very large data sets in a very compressed format - a gigabyte-sized Revit file can be compressed to a DWF that's small enough to email Retains information associated with building components from Revit file Accurate 3D representation of a BIM - DWF users can navigate, rotate, cut by cross-section, and measure dimensions in a saved 3D view Allows users to mark up the DWF - software allows users to make comments and notes to the DWF and keeps track of all mark ups for easy input back into the Revit file.	Autodesk Design Review	Ability to manipulate, navigate, and review a 3D Model
Storage and Retrieval of BIM data	**The BIM in Facilities Management** Ronald Mendez	The intent of this thesis was to explore ways to publish BIM data in an easy and accessible manner.The study developed an internet website that contained a BIM-generated 3D model and samples of the O&M manuals and warranties.	Demonstrated the storage of digital closeout documents, while maintaining a link to the Revit file. Provided recommendations of a developing a more secure storage system and establishing links between the physical Revit model and its digital closeout documents.	Autodesk Revit Digital versions of closeout documents	Ability to navigate and review a 3D Model Requires the ability of computer filing navigation
Feasibility of Implementing Autodesk Revit	**Autodesk Revit: Implementation in Practice** Lachmi Khemlani	The intent of this white paper was to provide detailed information on how Revit is currently being implemented into BIM practices and some key insights into the successful deployment of Revit and BIM.	Determined Revit's key strengths and identified the challenges involved in implementing it, and gauged the impact of Revit deployment on Owner's processes. Found that users had a strong liking for Revit and its capabilities in spite of challenges during implementation. For some, "Revit was easy to learn and use, while others described a steep learning curve even for tech-savy users." 3-4 month learning process. Respondents described Revit as "the first car to the first horse," and having experienced the speed, efficiency, and effectiveness of the car ride, none of these users want to go back to using the horse.	-	-

According to the research of Section 4.2, the management of paper library information exchanges is a technically difficult and time-consuming activity for the Department. Use of Autodesk Design Review and its DWF files will allow facilities managers to provide intelligent building information in 3D views to its Maintenance & Repair teams for work orders. Objects from the record BIM and its digital library are furnished with specific properties (height, width, operating requirements, and so forth) and all of their O&M documentation.

While the amount of information stored within a record BIM is extensive, the Department will be capable of extracting the relevant information from the BIM for the purposes of the work order. Repairs and comments addressed by the Maintenance & Repair teams can be published within the DWF as BIM-interpretable information and automatically imported into the record BIM. This proposed process improves productivity by providing fast and accurate information and permits the use of computer tools to assist in managing and storing the data. While this is somewhat of a circular process, shown in Figure 18, the continual update of service on the building and its assets produces a valuable up-to-date model for the Department's reference throughout the lifecycle of the building.

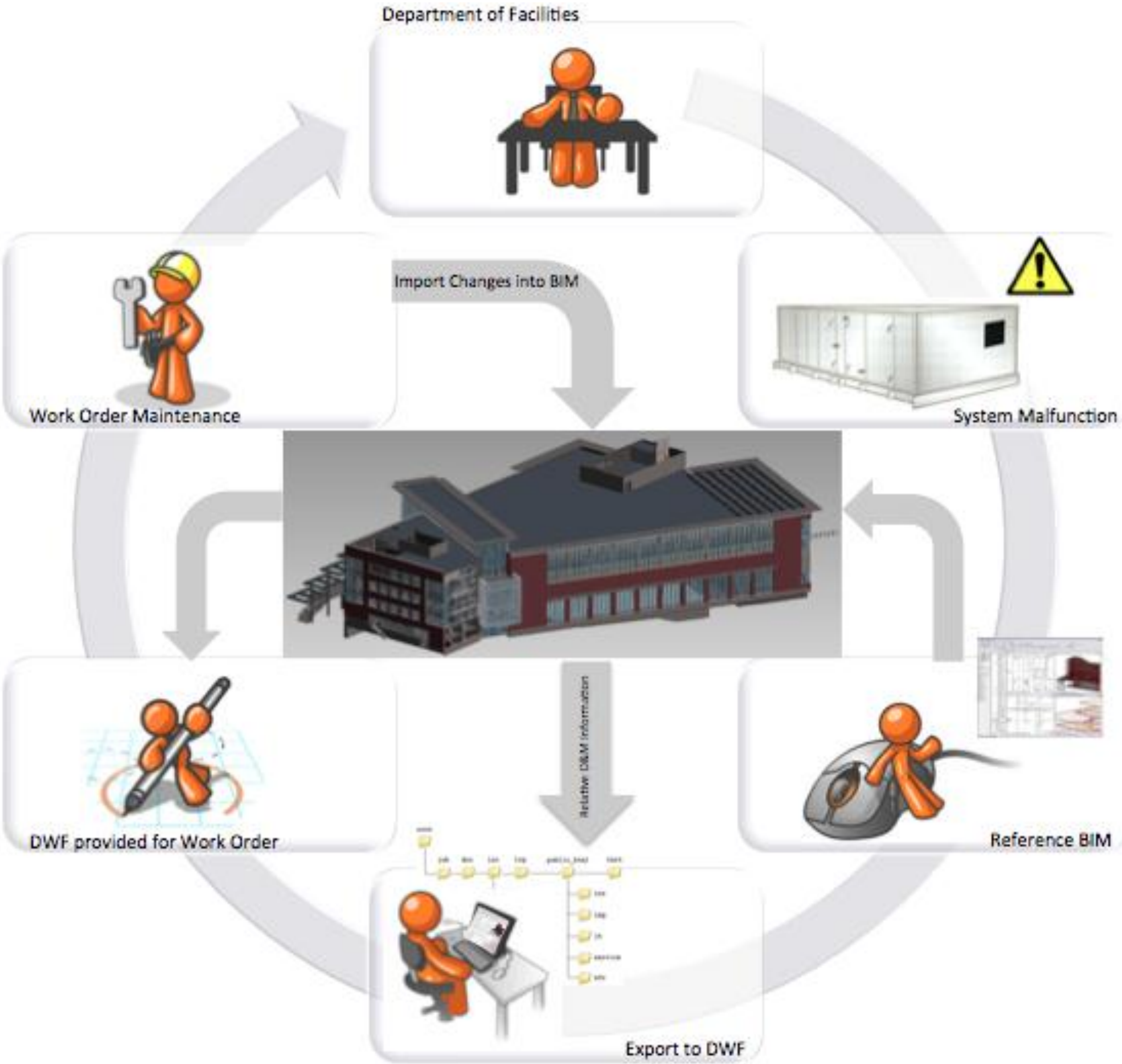

Figure 18: Cycle of Using BIM in Facilities Management

4.4 Facilities Management and Structural BIM Prototypes

For the purpose of demonstrating the capabilities of BIM technology and its adaptive qualities for both the design and post-construction phases of a project, two three-dimensional models were created using Autodesk Revit. One model displays BIM's potential uses for facilities management, developed from the results of Sections 4.1 through 4.3, while the second model demonstrates BIM as a visual aid for exploring structural alternatives in the design phase. The BIM developed for the Department of Facilities contains the essential closeout documentation, found in Section 4.1, stored within the model's components. The respective O&M information was tagged to each component within the model to allow for convenient retrieval of information by the Department. Use of a BIM for the purposes of facilities management warrants the storage and retrieval of digital information without referencing the expansive paper library currently used by the Department.

The prototypes were created using Autodesk Revit Systems, primarily Revit Architecture and Revit Structural. As discussed in the Background, Revit allows users to create 3D models capable of combining the various aspects of a construction project to aid in the coordination of the trades work. Architectural models can be imported with structural, MEP, and even fire protection models to create a record model that includes all of the respective information associated with the systems. Furthermore, Revit's ability to tag components with attributes allows information to be digitally stored within the model and retrieved in a convenient and organized fashion.

4.4.1 BIM Prototype for the Department of Facilities

While the record model was developed using Autodesk Revit software, Autodesk Design Review was used to present the model. This software addresses the concern of the Department of Facilities in having a user-friendly interface that doesn't require classes or other forms of extensive training for daily-use. Autodesk Design Review allows the user the ability to manipulate the model and access the information stored within its components. This more intuitive software permits virtually anyone to utilize the 3D model as a source of information critical to the function of the Department of Facilities. Another advantage to Design Review format is that its associated DWF files are significantly smaller than .rvt files. The smaller file size allows for convenient storage and transfer of information amongst the Department personnel without sacrificing the data embedded within the model. Autodesk Design Review software is also free to install and use on any computer, compared to the expensive licenses for Revit per use by each computer. However, Design Review software is not without its limitations. For instance, physical changes cannot be made to the model through Design Review - information can only be accessed, viewed, and commented on. Any changes necessary to the model would require editing the .rvt model and then re-exporting the model as a DWF file. Figure 19 shows the prototype of the mechanical room from the new Center displayed in Autodesk Revit, while Figure 20 shows the room in Design Review.

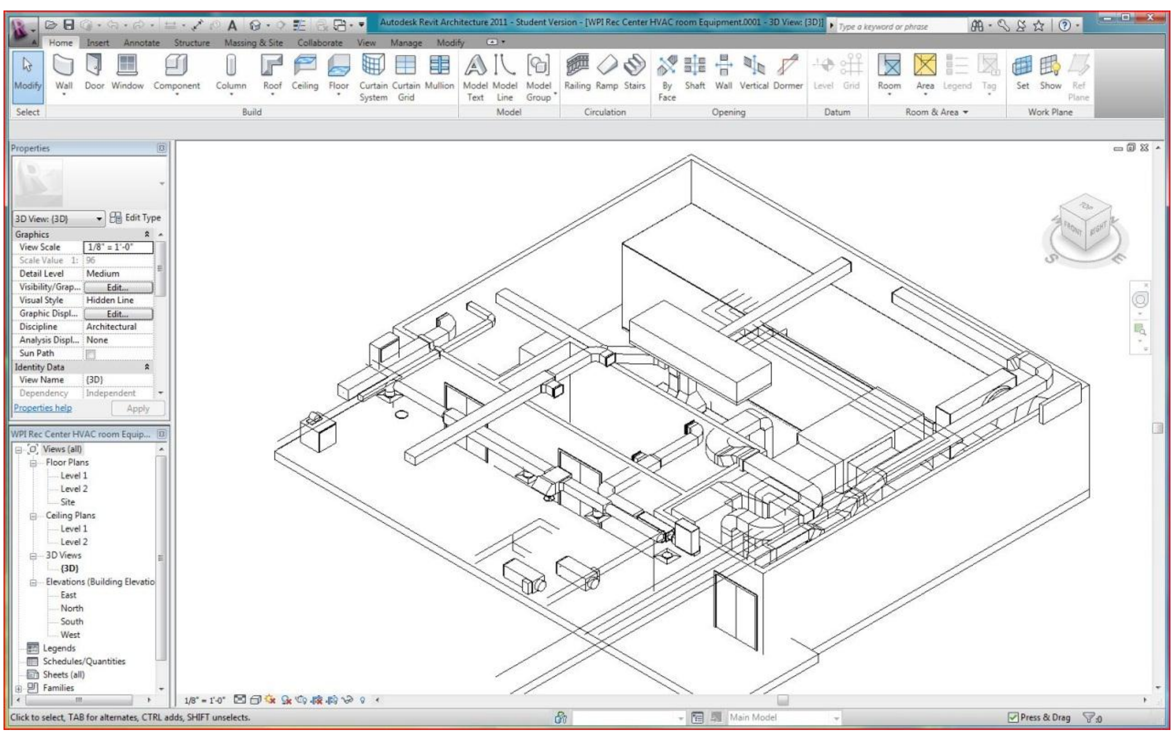

Figure 19: BIM Prototype for the Department using Autodesk Revit

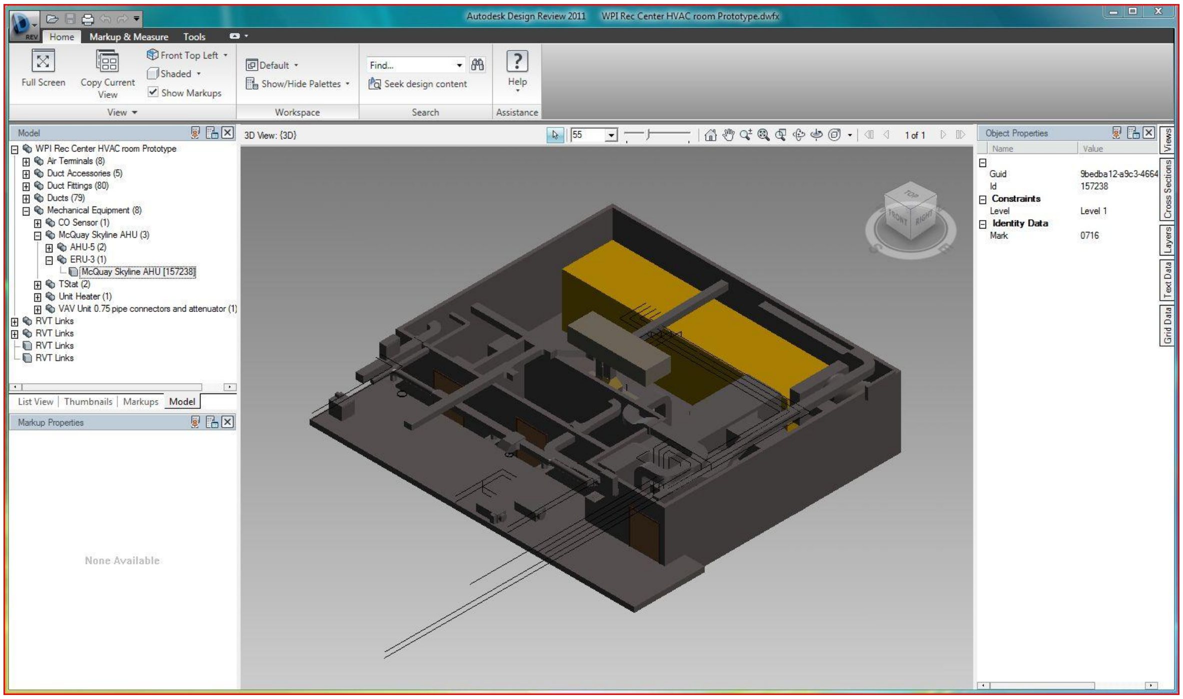

Figure 20: BIM Prototype for the Department using Autodesk Design Review

In order to demonstrate the power of BIM technology for Asset Management (see Section 4.3), information critical to the processes of the Department was stored within the model. The developed BIM addresses the current issues and limitations of the paper library with a convenient storage method and time-efficient retrieval process for work orders. However, using WPI's new Sports and Recreation Center as a basis for the prototype has had minor complications. With the Project currently in the construction phase, Gilbane has not yet compiled all of the closeout information, as it was too early in the process. As a solution to this obstacle, information was collected from various manufacturer web sources, true to the types of equipment actually furnished in the new Center, and used within the prototype for demonstration, as a proof of concept.

The digital closeout information that couldn't be tagged to the components was linked within the model to an organized file database. PDF versions of the O&M manuals, warrantees, and submittals were stored in this digital library. Traditional two-dimensional floor plans and Project Specifications were also incorporated into the database for reference. The digital library was organized into a local computer database, per suggestion of *The BIM in Facilities Management* by Ronald Mendez.(2006) Local storage of the database on a server was felt to be a more secure method because the information can be accessed in emergency situations such as power outages and Internet crashes.

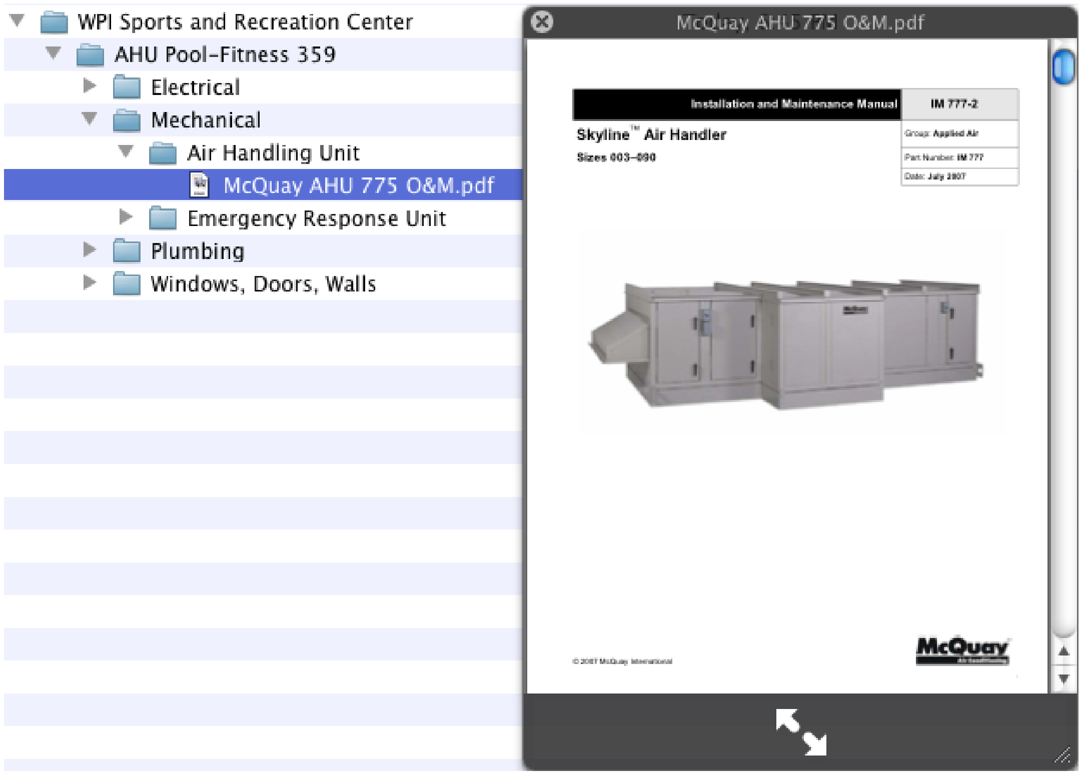

Figure 21: Digital Database

4.4.2 BIM Prototype Usage Walkthrough

In order to enhance the usability of the prototype for the Department of Facilities, the procedure required to identify equipment and access its closeout and O & M information was designed to be relatively simple. The procedure begins with opening the model in Autodesk Design Review. Next the user would navigate through the structure and locate the piece of equipment or component that is of interest. Once the component is located, a click of the mouse will select it. The item will become highlighted to indicate its selection. By scrolling to the right side of the screen and clicking the "Object Properties" tab, a list of the component's attributes will appear, Figure 22. Examine the listed attributes to find the desired information, Figure 23. If the information is not listed in the attributes, then click the appropriate link to be rerouted to the proper documents to locate the necessary information, Figure 24.

One difficulty that occurs with this process is that when a model is exported from Revit to Design Review, some of the component information is not transferred over. The information that gets left behind is dependent on the component that is in question. The incorporated information doesn't tend to follow any specific pattern that determines what information is transferred over and what is left behind.

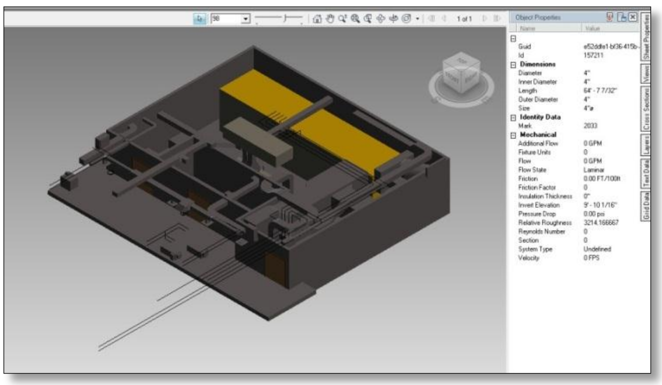

Figure 24: Model with Single Component Attributes

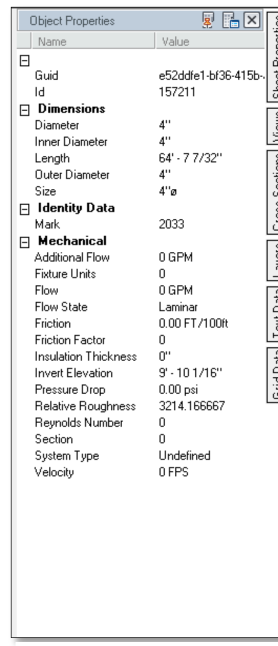

Figure 23: List of Attributes

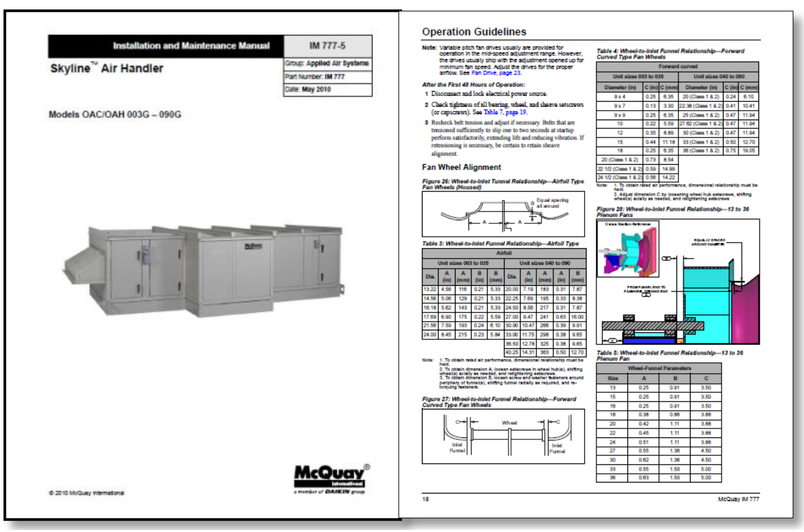

Figure 22: Information Linked from List of Attributes (McQuay International)

Due to this slight information gap between the attributes that are contained within the Revit Model and the information which is exported into the DWF model, the information that is not successfully transferred will require additional steps to retrieve. Common solutions to retrieve this data include either opening the Revit Model, or manually entering the information database and locating the desired information.

4.4.3 BIM Prototype for Structural Alternative #2

The use of BIM as a visual aid and coordination technology for structural design was the focus of the second prototype. This model displays the potential uses of BIM in both the design and construction phases, as used by the Project Team in their coordination meetings. As an alternative to the current precast arches of the new Center, a steel truss system was constructed with Autodesk Revit Structural, shown in Figure 25. This model allows individuals involved on the Project, who do not have extensive knowledge in every construction trade, to understand the coordination of their work with other trades and the physical structure. Using BIM during the design phase also allows the Owner to understand the layout of floor plans and weigh the aesthetics of the design alternatives. Development of the structural alternatives is discussed in Chapter 5. The design portrayed in Figure 25 is that of Alternative 2, a steel truss system designed to accommodate the vertical loads supported by the precast concrete arches. Figure 26 is the trusses designed in Alternative 2 imported to Cannon Designs rendering of the natatorium.

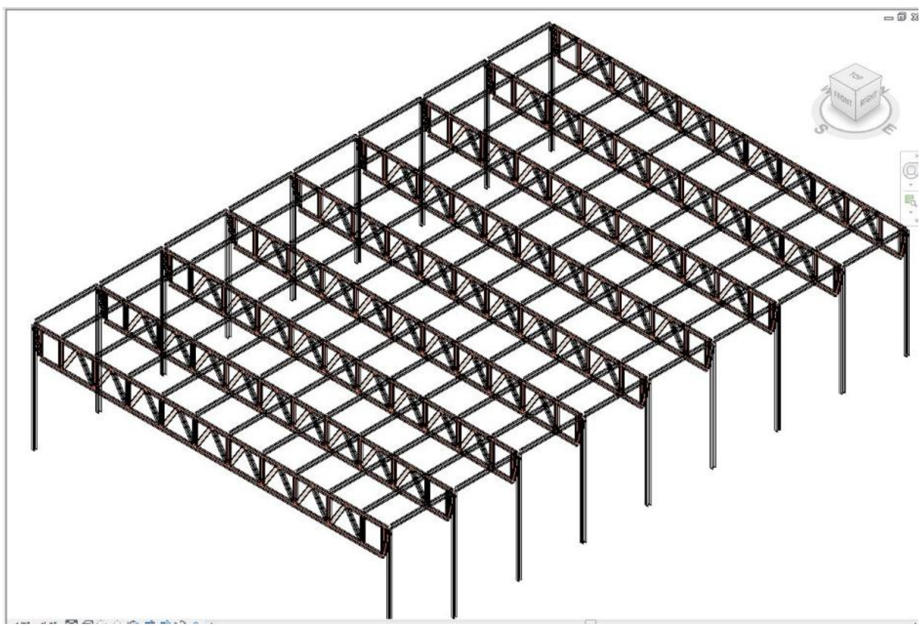

Figure 25: Structural Alternative 2 Shown in Revit

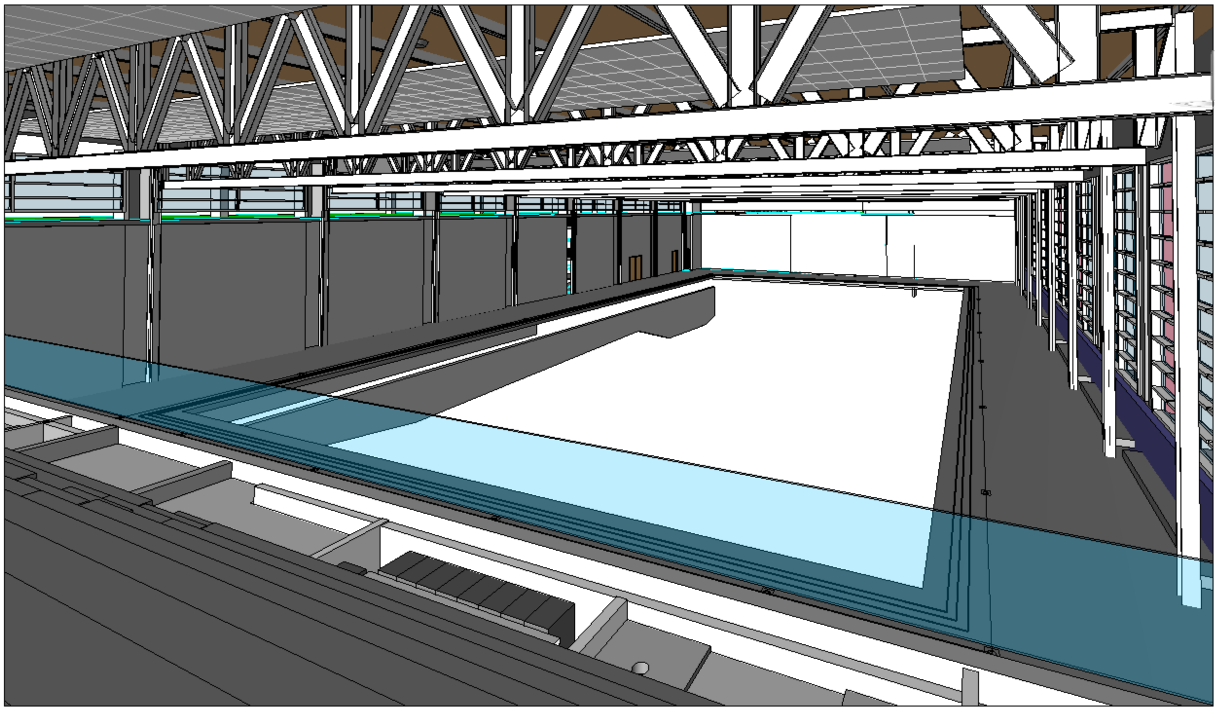
Figure 26: Free Standing Truss (Alt 2) Rendering

5.0 – Structural Alternative

The goal of designing an alternative to the precast concrete bents in the natatorium was to create a structure that could be substituted for the arch system and to develop a cost and schedule that could be compared to the current system. In order to accomplish this goal, the following tasks were established:

- Design a competitive floor system to replace precast double tee-beams
- Design alternatives to the concrete bents
- Develop a cost estimate for each alternative
- Establish a schedule for each alternative

These tasks contributed to investigating the feasibility of an alternative for the existing structural system in the natatorium. Structural member sizes and connection details were developed for three different alternatives. Additionally these tasks allowed the alternatives to be compared to the existing structure by cost and schedule.

5.1 Composite Floor System

The floor system of the gymnasium to replace the concrete slab and precast double-tee beams was designed to be a partial composite system. This system will consist of a cast-in-place concrete slab over steel decking supported by W-shape floor beams or joists, which span the natatorium in the East-West direction. A plan view of the natatorium with floor joist spacing for Alternative 1 and 2 is shown in Figure 27. Alternative 3 has similar spacing, yet column locations are different since the truss spans a longer distance. A cross-sectional drawing of this system is displayed in Figure 28. The system properties and results obtained are presented in Table 9. All design calculations can be found in Appendix C.

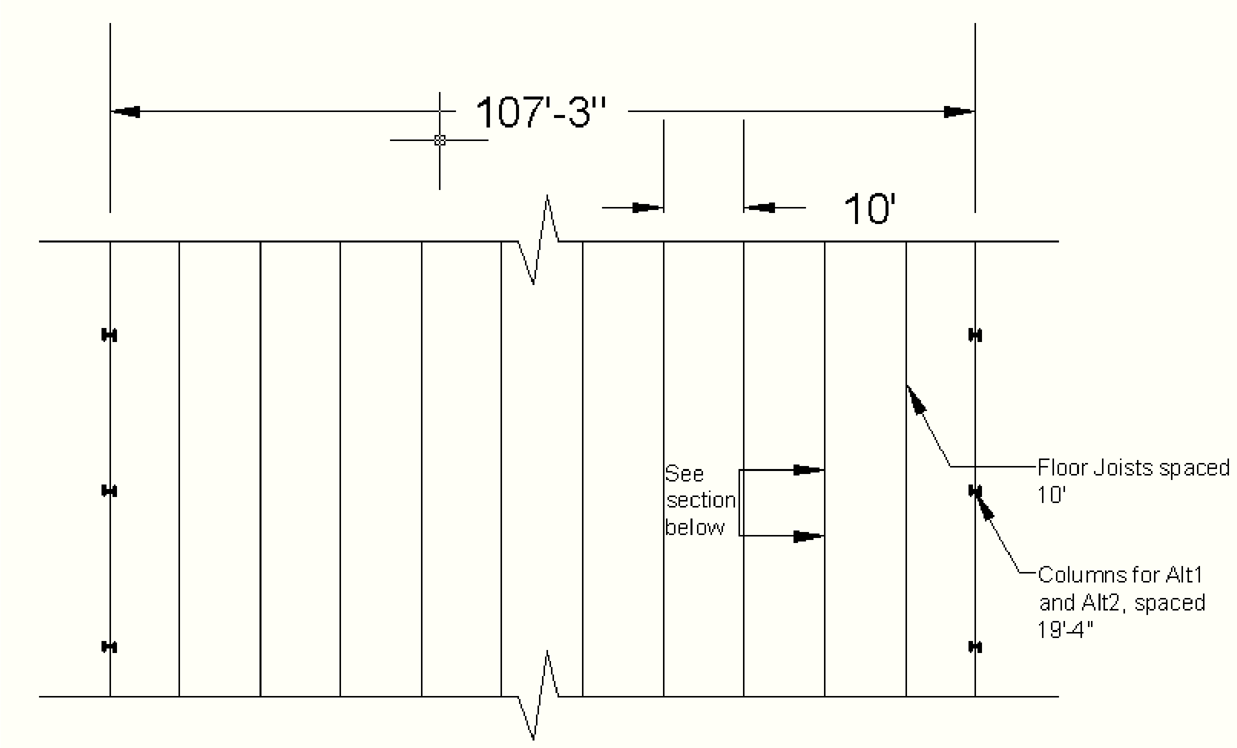

Figure 27: Plan View of Natatorium with Floor Joists and Columns

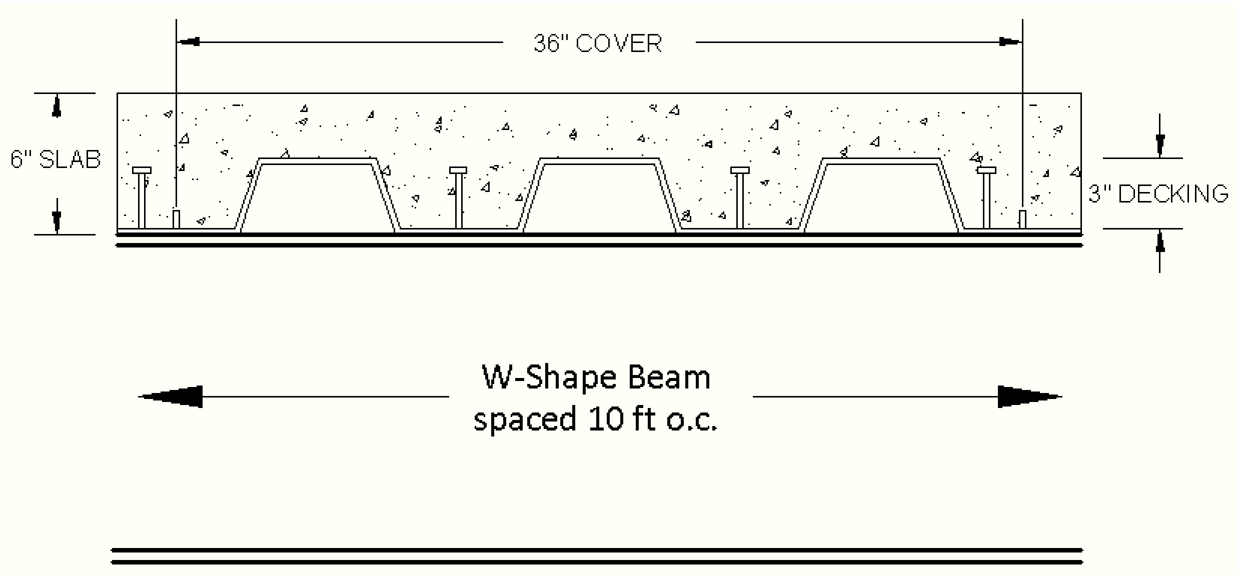

Figure 28: Composite Gymnasium Floor System

Table 9: Gymnasium Floor System Results

Gymnasium Floor System: Input/Constraints		
Design Element	Proposed Solution	Comments
Type of Floor System	Partial Composite	Similar to systems throughout building and may reduce cost since fewer shear studs are used.
Concrete Slab	Thickness: 6 in. Strength: F'c = 4000 psi Unit Weight: 145 pcf	Existing slab above double T-beams is also 6" thick with the same strength and weight properties
Steel Decking	Manufacturer: Vulcraft Deck Type: 3VLI18 Height: 3 in. Thickness: 0.0474 in. (18 gauge) Unit Weight: 2.84 psf Unbraced Span: 10 ft. (1 or 2 span)	Existing systems throughout building use 3", 18 gauge or 20 gauge decking with similar section properties to the chosen Vulcraft steel decking. Span determined from Vulcraft catalog.
Floor Joist Properties	Max Unbraced Length: 24 ft. Spacing/Effective Width: 10 ft. Yield Strength: F_y = 50 ksi	
Loads	LL – 100 psf (Gymnasium) = 1000 lb/ft DL – 944.8 lb/ft plus girder weight, determined from: Concrete = 766.3 lb/ft Decking = 28.5 lb/ft MEP & Ceiling = 150 lb/ft	
Shear Stud	¾" diameter studs	Same stud parameters are used in the existing building, according to Cannon's Structural Drawings
Gymnasium Floor System: Design		
Design Element	Proposed Solution	Comments
Concrete Slab	Thickness: 6 in. Strength: F'c = 4000 psi Unit Weight: 145 pcf	Existing slab above double T-beams is also 6" thick with the same strength and weight properties
Steel Decking	Manufacturer: Vulcraft Deck Type: 3VLI18 Height: 3 in. Thickness: 0.0474 in. (18 gauge) Unit Weight: 2.84 psf Unbraced Span: 10 ft. (1 or 2 span)	Existing systems throughout building use 3", 18 gauge or 20 gauge decking with similar section properties to the chosen Vulcraft steel decking. Span determined from Vulcraft catalog.
Floor Joists	W 14 x 34 Spacing: 10ft	Using AISC Manual T. 3-19
Shear Stud Spacing	24 ft. Span: 12 studs spaced 24 in. o.c. 19'-4" Span: 10 studs spaced 24 in. o.c.	To match existing constraints set by Cannon Design, stud spacing cannot exceed 24 in.

This floor system design will be a part of all three alternatives. All associated loads will be transferred from the floor system to the alternatives through the W14x34 joists.

5.2 Alternative 1 – Free Standing Frame System w/ Girder

The first alternative analyzed was a simple pin-supported portal frame system using two vertical W-shaped columns to support a horizontal W-shape girder, shown in Figure 29. The girder supports the gymnasium floor above, designed in Section 5.1. Since the girders are evenly spaced at 10 ft o.c., the load acting on the frame was treated as uniformly distributed. The system properties and results obtained are presented in Table 10, while the connection designs are presented in Table 11. All supporting calculations can be found in Appendix C.

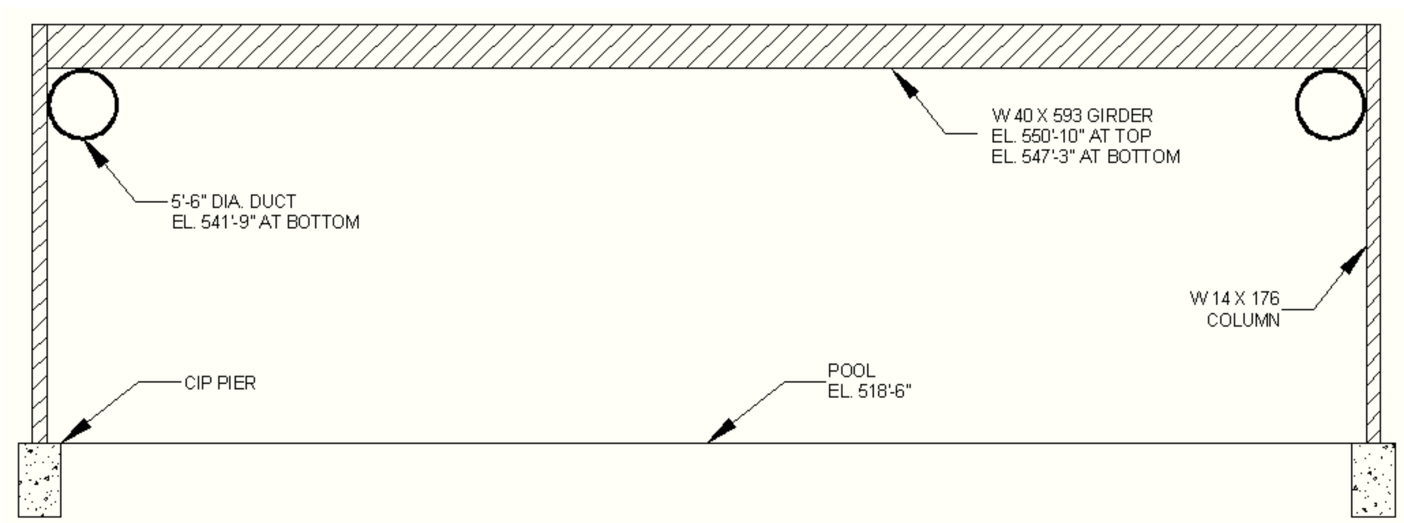

Figure 29: Alternative 1 System with MEP and Footings

Table 10: Frame System w/ Girder Results

Alternative 1: Input/Constraints		
Design Element	Proposed Solution	Comments
Girder Properties	Total Length: 107.33 ft. Unbraced Length: 10 ft. Spacing/Effective width: To match existing arches – max of 24 ft. Yield Strength: F_y = 50 ksi	Placement reflects location of existing arches.
Girder Loads	LL – 100 psf (Gymnasium) = 2.4 k/ft DL – 2.301 k/ft plus girder weight, Determine from: Concrete = 1839 lb/ft Decking = 68.16 lb/ft MEP & Ceiling = 360 lb/ft Floor System Girder = 34 lb/ft Governing Load Combination W_u = 1.2D + 1.6L = 6.6 k/ft Uniform Load = 708.38 k	
Girder Moment	Max moment = 9711 ft-kips	Moment analysis governed size of beam.
Column Properties	Total Height: 32'-4" Effective Length (assume K=1): 32'-4" Yield Strength: F_y = 50 ksi	
Column Loads	LL – 100 psf (Gymnasium) = 132 k DL – 159.1 k determined from: Concrete = 101.1 k Decking = 3.7 k MEP & Ceiling = 19.8 k Floor System Beam = 1.9 k Frame Girder = 32.6 k DL from above columns – 770 k P_u = 1172.12 k	

Alternative 1: Design		
Design Element	Proposed Solution	Comments
Girder Design	W 40 x 593	Using AISC Manual T. 3-2
Column Design	W14 x 176 Short and non-slender	
Base Plate Design	A36 Grade 42 18" x 18" Plate 2" thick P_u = 1175 k	According to Cannon Drawings S001, all base plates are A36 Grade 42 and are grouted
Weight of System	376.63 tons of steel	

Table 11: Frame System with Girder Connections

Alternative 1 Connections	
Floor System Beam – Girder	16.7" x 8.75" Plate 1" thick A36 Steel Use 4 bolts – ¾" diameter – A325N V_u = 66 k
Girder – Column	2L 3½ x 3½ x ½ Double Angle L=24.5 in. A36 Steel Use 6 bolts – 1" diameter – A325N V_u = 390 k

With a W-shape girder, the existing duct system will be suspended below the girder, near the ends of the span. The existing duct hangs 24'-9" above the pool, at an elevation of 543'-3". If a W40x593 were used, the duct would hang about 23'-3" above the pool. Figure 28 shows how the system would look with the ducts above the pool.

5.3 Alternative 2 – Free Standing Truss

This design consists of two vertical W-shaped columns supporting a truss system. The truss system supports the gymnasium floor above, however uses more components and different shapes than Alternative 1. Vertical components were added to a Warren type truss at the locations of the W13x34 floor joists, and the joists convey point loads on the truss at panel points. This geometry is similar to that of the existing steel truss above the gymnasium, supporting the roof of the new Center. A section of the proposed floor system with the truss is presented in Figure 30.

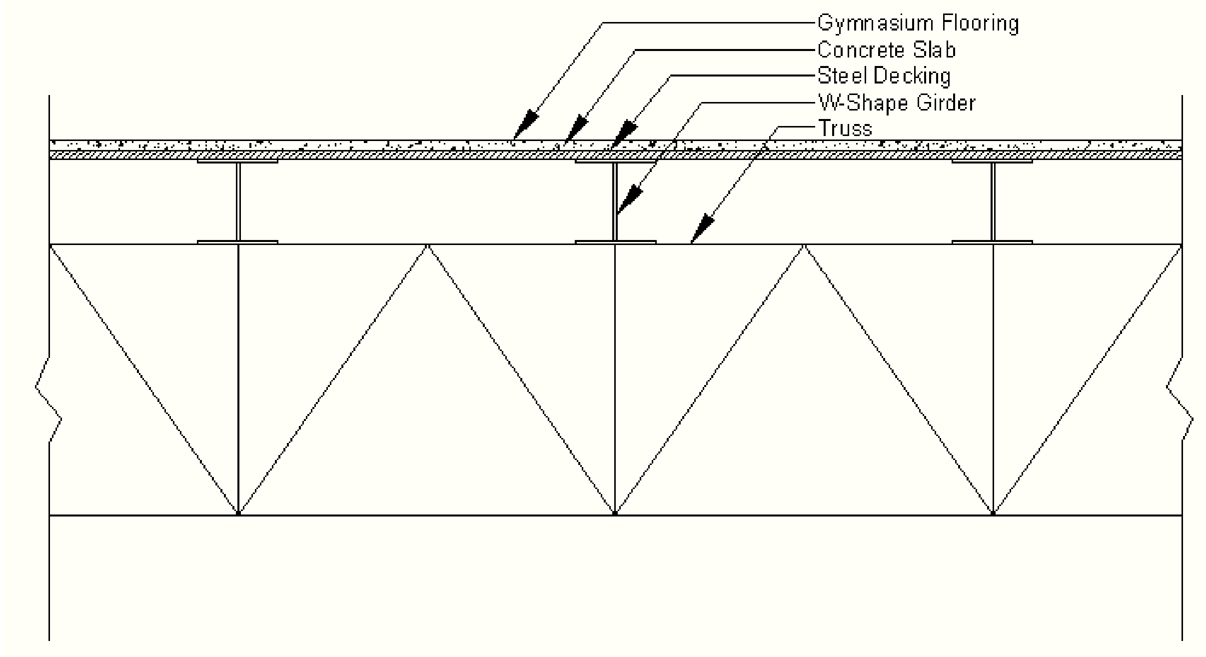

Figure 30: Alternative 2 with Floor System

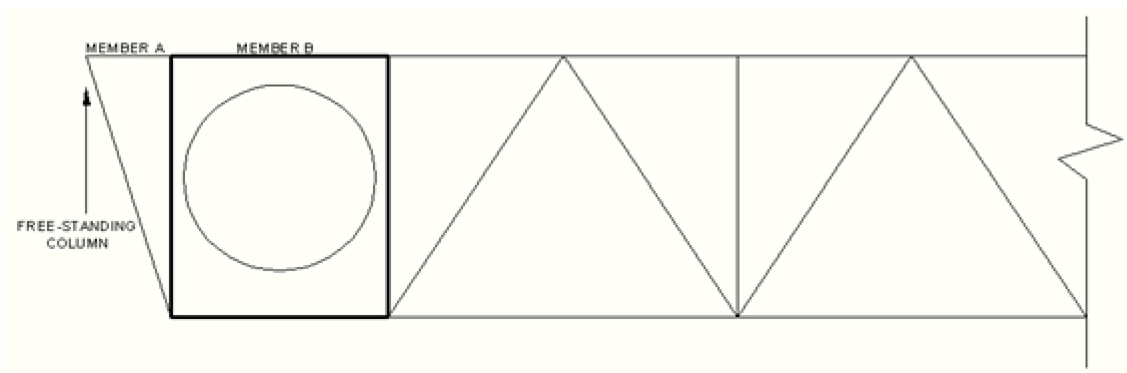

Figure 31: Alternative 2 Truss/Frame System

Since the MEP duct must intersect the truss on the outsides, the truss becomes broken at the ends of its span. A frame system is designed at these locations due to the MEP constraint so that the duct can travel the length of the natatorium without interrupting any structural components. This section of the system is shown in Figure 31.

The truss system design for Alternative 2 is shown in Figure 32 and all properties and results obtained are presented in Table 12. All calculations are represented in Appendix C.

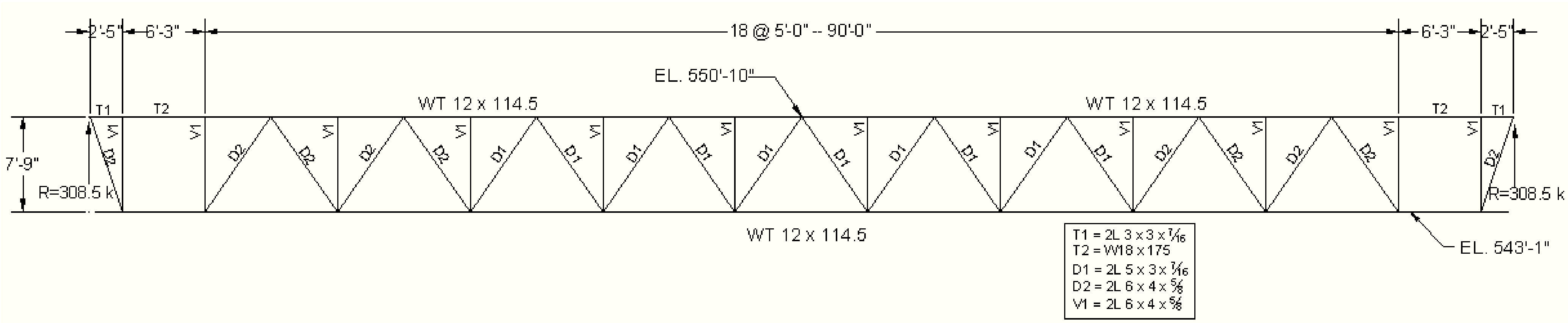

Figure 32: Free Standing Truss Layout and Member Sizes

Table 12: Free Standing Truss Results

Alternative 2: Input/Constraints		
Design Element	Proposed Solution	Comments
Truss Properties	Total Length: 107'-3" Total Depth: 7'-9" Unbraced Length: 10 ft. Spacing/Effective width:= max of 24 ft.	Placement reflects location of existing arches. Depth of arches is only 5'-9".
Truss Loads	All loads are same as the Girder Loads in Table 10. Governing Load Combination Wu = 1.2D + 1.6L = 6.6 k/ft Point Loads at Floor Girders (10 ft o.c.): 59 k	
Top and Bottom Chord Properties	Max Effective Length: 10 ft Shape: -Bottom Chord & Truss Top Chord: WT Shape -Top Chord Frame – Member A: Double Angle -Top Chord Frame – Member B: W-Shape	Existing truss above gymnasium uses WT Shapes for top and bottom chords
Diagonal Member Properties	Max Effective Length: 8'-9" Shape: Double Angle	Existing truss above gym uses Double Angle Shapes for diagonal members
Vertical Member Properties	Max Effective Length: 7'-2" Shape: Double Angle	Existing truss above gym uses Double Angle Shapes for vertical members
Column Properties	Total Height: 32'-4" Effective Length (assume K=1): 32'-4" Yield Strength: F_y = 50 ksi	
Column Loads	LL – 100 psf (Gymnasium) = 132 k DL – 140.35 k determined from: Concrete = 98.7 k Decking = 3.65 k MEP & Ceiling = 19.3 k Floor System Girder = 1.8 k Truss = 16.9 k DL from above columns(Field Side) – 400 k P_u = 774.4 k DL from above columns (Quad Side) – 770 k P_u = 1144.4 k	

Alternative 2: Design		
Design Element	Proposed Solution	Comments
Truss Design	Refer to Figure 26 Top and Bottom Chord is WT 12 x 114.5 unless noted otherwise on drawing	Using AISC Manual T. 3-6
Column Design	Field Side: W14 x 132 Quad Side: W14 x 176	
Base Plate Design	A36 Grade 42 Field Side: 16" x 16" Plate, 1.75" thick P_u = 775 k Quad Side: 18" x 18" Plate, 2" thick P_u = 1145 k	
Weight of System	237.71 tons of steel	

Notice that there are two column designs: one for the field side and one for the quad side. This is because the columns from the above floors on the quad side are supporting more weight than those on the field side. Also notice (Table 12 – Truss Properties) that the depth of Alternative 2 extends below that of the existing arch system, allowing 24’-7” between the truss and the pool deck (at El. 518’-6”) compared with the 27’-9” allowed by the current system of precast arches. The ducts which run through the existing precast arches will also run through the proposed truss alternative. Although the bottom chords of the trusses extend lower than the arches at midspan; the ducts will need to be raised in order to fit through the truss’ web members. The bottom of the duct will hang at an elevation of 544’-2” as opposed to the current 543’-3”. A drawing of the designed truss with member sizes is shown in Figure 32. Note that member T2 is a W-shape laid about its minor axis.

Tables 13 and 14 summarize elements of the connections designed for the truss, columns, beams, and base plates. Most members of the truss are connected by fillet welds, while most other connections are bolted. Since the truss is so large, a T-Beam gusset plate was added to provide a larger connection from the truss to the column. Note that all bolts used are A325-N per the Cannon Design structural drawings. All supporting calculations can be found in Appendix C.

Table 13: Alternative 2 Bolted Connections

Alternative 2 Bolted Connections						
Location	***Plates/Angles Size***	***P/A Thickness***	***Bolt Dia.***	***# Bolts***	***Strength P/A***	***Vu***
Floor System Beam - Top Chord T-beam	13" x 9" Plate	1"	3/4"	4	F_y = 36 ksi	66 k
Floor System Beam - Top Chord T-beam/W-shape (Member B -Rest of Truss) *	20" x 7" Plate	3/4"	¾"	4	F_y = 36 ksi	66 k
T-Beam Gusset - Column	WT9x79 Gusset Plate L=27"	t_f = 1.44	1"	6	F_y = 50 ksi	308 k
Column - Base Plate	Fillet weld around column to base plate					
Base Plate - Footing	Anchor rods through concrete and baseplate - Grout baseplate					

*In order for the floor system beam to run perpendicular to the truss system, Member B (W-shape) must be coped at least 3.5" to fit the beam and its base plate. In addition, to prevent buckling or bending in the web of the W-shape (Member B) or the flange of the T-beam (rest of truss), stiffeners should be used. A detail of this connection is presented in Figure 33.

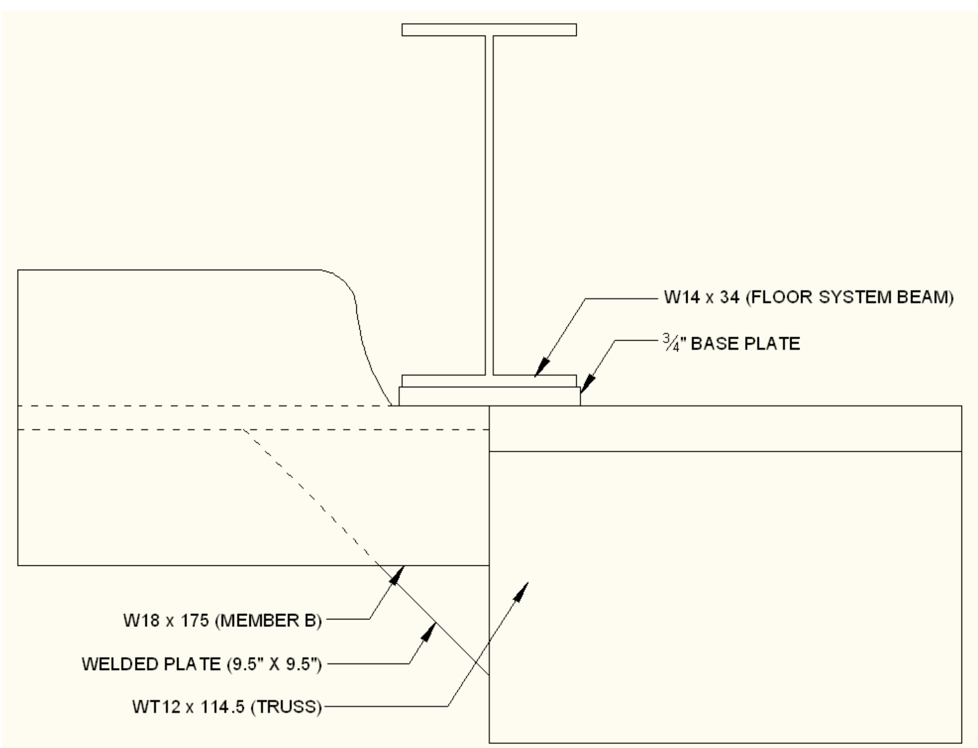

Figure 33: Connection of Floor System Beams and Member B/Rest of Truss

Table 14: Alternative 2 Weld Connections

Alternative 2 - Weld Connections (Fillet Welds, E70 Electrodes)			
Truss Connections	***Member Sizes***	***Weld Length (in)***	***Weld Capacity (kips)***
Diagonal Double Angle to Top and Bottom Chord T-Beam			
Inside (10 members)	2L5x3x7/16 to WT 12x114.5	11	150
Outside (8 members)	2L6x4x5/8 to WT 12x114.5	15	301
Vertical Double Angle to Top and Bottom Chord T-Beam	2L6x4x5/8 to WT 12x114.5	4	62
Frame Connections			
Diagonal Double Angle to Gusset T-Beam	2L6x4x5/8 to WT 9x79	15	301
Diagonal Double Angle to Bottom Chord T-Beam	2L6x4x5/8 to WT 12x114.5	15	301
Vertical Double Angle to Top Chord	2L6x4x5/8 to 2L3x3x7/16	5	62
Vertical Double Angle to Bottom Chord T-Beam	2L6x4x5/8 to WT 12x114.5	4	62
Top Chord Double Angle to Gusset T-Beam	2L3x3x7/16 to WT 9x79	3	36
Top Chord Double Angle to Top Chord W-Beam	2L3x3x7/16 to W 18x175	3	36
Top Chord W-Shape to Top Chord T-Beam	W18x175 to WT12x114.5	19	531
*Note: For top chord W-shape to top chord T-beam connection use 1 triangle shaped plates (9.5in x 9.5in), thickness = 0.96"			

5.4 Alternative 3 – Rigid Planar Truss

The design and geometry of Alternative 3 is very similar to that of Alternative 2; however, it is not free standing – it ties into the existing columns on one side. Alternative 2 is self-supporting in the sense that it is only responsible for transferring gravity loads, and columns were added to the existing design on both ends of the truss. Alternative 3 must support lateral loading along with gravity loads. This is because only one column was added to the existing design (on the field side) and the other end of the truss is supported by the existing structural columns. This increased the total span of the truss by 3'-3".

As previously discussed in Section 5.3, all alternatives must support the columns above which include loads from floors 3, 4, and 5. Since the column to support the truss on the quad side was displaced laterally 3'-3", the overlying columns had to be supported by the truss system, rather than on the supporting column. This changed the geometry of the frame part of the truss on the quad side. This new geometry is shown in Figure 34.

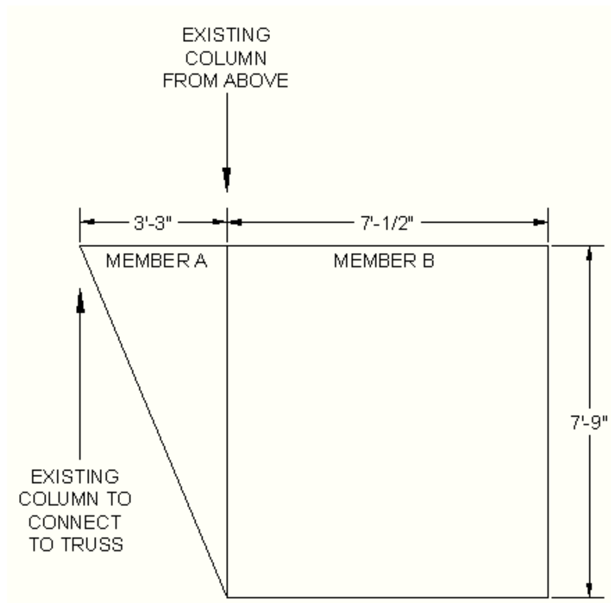

Figure 34: Alternative 3 Quad Side Frame Geometry

Similar to Alternative 2, Alternative 3 has a frame system incorporated into truss to allow for the MEP duct. There are also two different column designs and the depth of Alternative 3 extends below that of the existing arch system, allowing 24'-7" between the truss and the pool deck. The truss and frame system design for alternative 3 is shown in Figure 35 and all results obtained are presented in Table 15. All supporting calculations are in Appendix C.

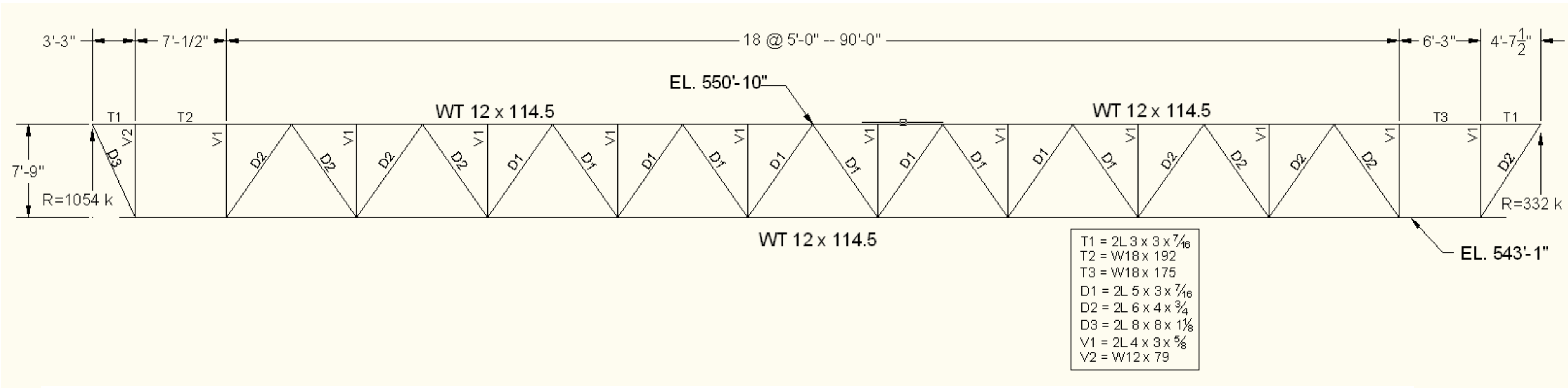

Figure 35: Rigid Planar Truss Layout and Member Sizes

Table 15: Free Standing Truss Result

Alternative 3: Input/Constraints		
Design Element	Proposed Solution	Comments
Truss Properties	Total Length: 110'-7" Total Height: 7'-9" Unbraced Length: 10 ft. Spacing/Effective width: max of 24 ft.	Placement reflects location of existing arches.
Truss Loads	All loads are the same as the Girder Loads in Table 10. Governing Load Combination Wu = 1.2D + 1.6L = 6.6 k/ft Point Loads at Floor Girders (10 ft o.c.): 60.8 k	
Top and Bottom Chord Properties	Max Effective Length: 10 ft Shape: -Bottom Chord & Truss Top Chord: WT Shape -Top Chord Frame – Member A: Double Angle -Top Chord Frame – Member B: W-Shape	Existing truss above gymnasium uses WT Shapes for top and bottom chords
Diagonal Member Properties	Max Effective Length: 8'-9" Shape: Double Angle	Existing truss above gym uses Double Angle Shapes for diagonals
Vertical Member Properties	Max Effective Length: 7'-2" Shape: Double Angle	Existing truss above gym uses Double Angle Shapes for vertical members
Column Properties	Total Height: 32'-4" Effective Length (assume K=1): 32'-4" Yield Strength: F_y = 50 ksi	
Column Loads	LL – 100 psf (Gymnasium) = 132 k DL – 140.35 k determined from: Concrete = 101.65 k Decking = 3.77 k MEP & Ceiling = 19.9 k Floor System Girder = 1.88 k Truss = 17.3 k DL from above columns(Field Side) – 400 k P_u = 785.72 k DL from above columns (Quad Side) – 770 k P_u = 1155.72 k	

Alternative 3: Design		
Design Element	Proposed Solution	Comments
Truss Design	Refer to Figure 29. Top and Bottom Chord is WT 12 x 114.5 unless noted otherwise on drawing	Using AISC Manual T. 3-6
Column Design	Field Side: W14 x 132 Quad Side: W14 x 176	
Base Plate Design	A36 Grade 42 Field Side: 16" x 16" Plate, 1.75" thick P_u = 785 k Quad Side: 18" x 18" Plate, 2" thick P_u = 1155 k	
Weight of System	241.61 tons of steel	

Table 16 shows the connections designed for the truss, columns, beams, and base plates. All members of the truss are connected by fillet welds, while most other connections are bolted. Since the truss is so large, a gusset plate was added to adequately connect the truss to the column on both sides. Note that all bolts used are A325-N per the Cannon Design structural drawings.

Table 16: Alternative 3 Bolted Connections

Alternative 3 Bolted Connections						
Location	***Plates/Angles Size***	***P/A Thickness***	***Bolt Dia.***	***# Bolts***	***Strength P/A***	***Vu***
Floor System Beam - Top Chord T-beam	13" x 9" Plate	1"	3/4"	4	F_y = 36 ksi	66 k
Floor System Beam - Top Chord T-beam/W-shape (Member B -Rest of Truss) **	20" x 7" Plate	3/4"	¾"	4	F_y = 36 ksi	66 k
Quad Side T-Beam Gusset – Column	WT12x73 Gusset Plate L=45"	t_f = 1.09	1"	14	F_y = 50 ksi	1054 k
Field Side T-Beam Gusset - Column	WT9x79 Gusset Plate L=27"	t_f = 1.44	1"	6	F_y = 50 ksi	332 k
Quad Side Existing Column from Above – Top Chord***	Angles: L3x3x3/8 L=6-3/8"	3/8"	¾"	4	F_y = 36 ksi	36.3 k
	Plate: 6" x 6-3/8"	1/2"	N/A	N/A	F_y = 36 ksi	36.3 k
Column - Base Plate	Fillet weld around column to base plate					
Base Plate – Footing	Anchor rods through concrete and baseplate - Grout baseplate					

**Similar to Alternative 2, Member B (W-shape) must be coped at least 3.5" to fit the beam and its base plate. This connection follows the same detail as Alternative 2, shown in Figure 33.

***This location is at the joint where the above column is supported by the frame of the truss. One side of the top chord is a double angle (Member A - 2L 3 x 3 x 7/16), while the other side is a W-shape (Member B - W 18 x 192). Figure 36 depicts a cross section of this connection, while Figure 37 shows the plan view.

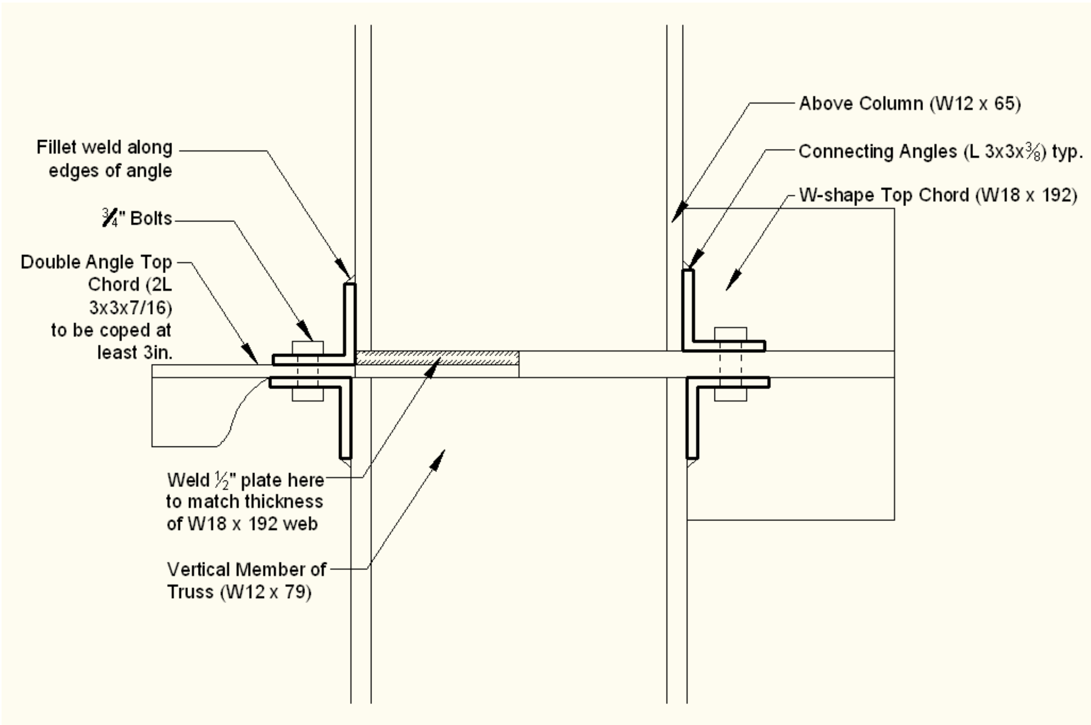

Figure 36: Alternative 3 Member A-Member B with Above Column and Vertical Member Cross Section

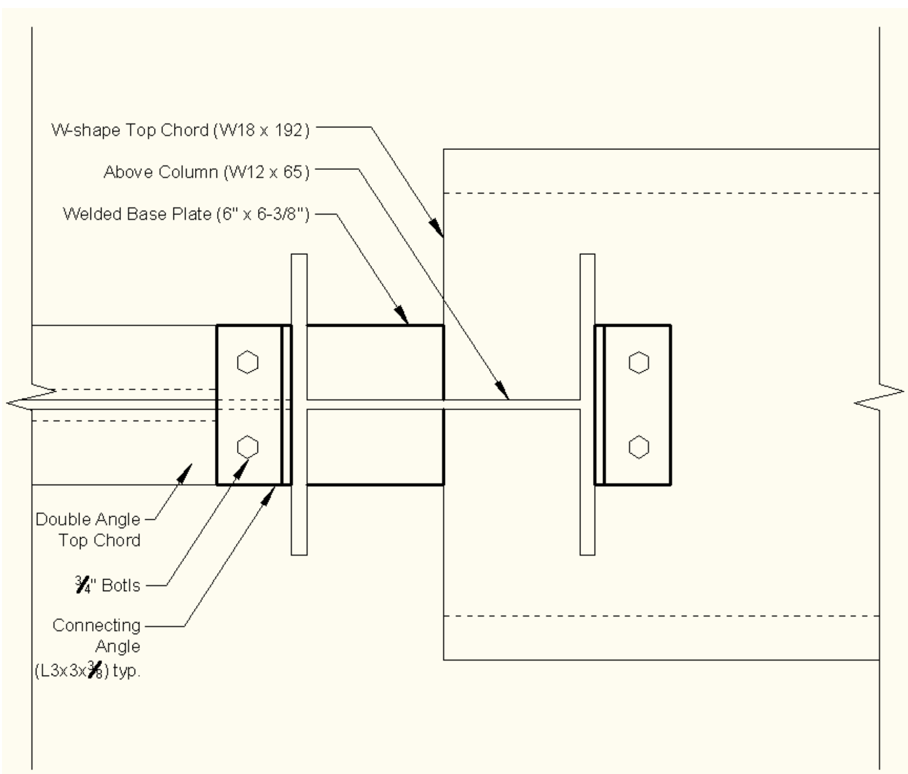

Figure 37: Alternative 3 Member A to Member B with Above Column Plan View

5.5 Cost Estimate

Based on methods outlined in Section 3.2.5 cost estimates were prepared for the three alternatives. The cost estimates were based off of information received from Gilbane and RS Means cost data. (RS Means, 2006) Gilbane estimated $2000/ton for structural steel and $1.5 million for the existing precast system. These costs include: material, fabrication, delivery, equipment, and labor and are presented in Table 17. Based on this data, steel is a less expensive material. Out of all the alternatives, alternative two is the most economical design amongst all of the alternatives.

Table 17: Cost Analysis Results

Costs				
System	Labor	Material	Equipment	Total
Alternative 1	$108,400	$731,650	$63,230	$903,280
Alternative 2	$75,050	$506,590	$43,780	$625,420
Alternative 3	$75,800	$512,620	$44,210	$632,630
Existing	$165,000	$1,232,250	$102,750	$1,500,000

5.6 Scheduling

A schedule estimate was developed for each alternative based on productivity data provided by GIlbane. The estimated man-hours for erection of the existing system was 1920 hours (6 weeks) for a 8 man crew. The estimated man-hours for erection of the roof trusses was 1280 hours (4weeks) for a 8 man crew. To determine the man-hours for the structural steel alternatives the estimated man-hours for erection of the roof trusses was analyzed. Using the total weights of each system a production rate was calculated to be 0.134 tons or 268 pounds of steel per hour. Based off of this production rate the man-hours were calculated for each alternative, shown in Table 18. Alternative two would take the least man-hours to erect (about 150 hours less than the existing system) while alternative one would take almost 900 more hours to erect. In addition, Gilbane will assemble the roof trusses as part of erection while Alternative 1 will require splicing sections of the W-shape together which may be more intensive than the trusses. Based on production rates and man-hours, a schedule was developed, shown in Table

19. Alternative two, which required the least amount of man-hours would be able to finish three days before the completion of the existing system. This would put less pressure on project deadlines and milestones. For example, it would allow for more time to place the decking slab of the gymnasium floor in case of weather setbacks.

Table 18: Man-Hours for Each System

Man-Hours	
Alternative 1	2810 hours
Alternative 2	1774 hours
Alternative 3	1797 hours
Existing System	1920 hours

Table 19: Estimated Schedule for Existing Precast and Alternative 2

Schedule		
System	Existing	Alternative 2
Start Date	November 1, 2010	November 1, 2010
End Date	December 10, 2010	December 7, 2010
Duration	6 Weeks (30 Days)	5.5 Weeks (27 Days)

5.7 Determining Preferred Design

The alternatives and existing systems were evaluated using the criteria discussed in Sections 2.4.4 and 3.2.6. This criteria included assessing each system by cost, schedule, maintenance, aesthetics and constructability on a scale of 0 – 3 (with 0 being the lowest and 3 the highest possible score). The subtotals were then summed for each system to yield an overall score. A summary of each evaluation is presented in Table 20, where it is shown that Alternative 2 received the highest score and therefore is the preferred solution. The evaluation of the existing solution and the three alternatives are discussed below.

The existing system of precast concrete received a zero for short term cost, and a three for long term cost. The total cost received from Gilbane was $1.5 million for the arches and double T-beams to be cast and delivered to the site. This cost is considerably high when compared to the price of steel. The concrete requires very little to no maintenance and because of its added fire safety and durability reduces insurance premiums. The existing system had a large effect on the schedule of the new Center construction. For this it receives a zero. The structural steel erection had to be halted for six weeks to allow for the placement of the precast concrete and the grouting of its connections. When evaluated for maintenance the precast received a three because of concretes durability, fire and corrosion resistance. The concrete was also coated in Tnemec paint for added corrosion resistance; overall the existing system will require minimal maintenance. For the category of aesthetics concrete received a three. As long as the concrete is properly finished, concrete has a smooth look to it and can be painted to match any color. Additionally the arches are an appealing shape with no sharp edges. Finally the existing system was rated on its constructability. For this it received a one because the precast pieces can be lifted right off the delivery truck and set in place. However, concrete is a very heavy material and requires a larger crane to lift the pieces into place. The pieces then must be grouted together over several weeks, prolonging the actual completion of the precast installation.

Alternative 1 received a one for short term cost and a two for long term cost. Alternative 1 was the most expensive of the alternatives; however, the estimated cost was still much less than the existing system. Alternative 1 would have a higher insurance premium than concrete because of its lack of durability and lower fire resistance. The erection of structural steel would not have to be halted with Alternative 1. For this, Alternative 1 received a three for schedule. Structural steel would require annual maintenance for fireproofing/corrosion-proofing because of its lack of durability in a humid climate. Some coatings that can be applied to steel to prevent corrosion and increase fire resistance are

Albi Clad 800 with primer and NanoChar. (Albi Manufacturing, 2011) (Intumescent Associates Group, 2011) The thickness of these coatings would have to be inspected annually to ensure it complies with code requirements. For this, Alternative 1 received a one. The first Alternative is a simple design with only girders spanning the natatorium; however, without any place to accommodate the MEP system required for the natatorium, the MEP ducts would have to hang from the girders and could be visually unsatisfactory. Additionally the fireproofing/corrosion-proofing cannot be changed in color and is an off white. For this, Alternative 1 received a one. Alternative 1 could be delivered in a similar manner as to the existing system, in pieces, and then could be constructed directly off the trucks. Because steel is a lighter material than concrete a smaller crane could be used for the steel erection. Alternative 1 weighted about 400 tons, which is about a third of the weight of the existing system. For this, Alternative 1 received a two.

Alternative 2 received a three for short term cost and a one for long term cost. Alternative 2 was the least expensive alternative. Similar to Alternative 1, Alternative 2 would have a higher insurance premium than concrete because it is constructed of steel. Alternative 2 will also have a higher long-term maintenance cost because the trusses have a larger exposed surface area and more exposed connections. The erection of structural steel would not have to be halted with Alternative 2; the trusses could be prefabricated and constructed then shipped to the site in pieces. Alternative 2 would only take 5.5 weeks to install. For this, Alternative 2 received a three for schedule. Similar to Alternative 1, Alternative 2 is fabricated from structural steel and would require annual maintenance for fireproofing/corrosion-proofing because of its lack of durability in a humid climate. As suggested for Alternative 1, Albi Clad 800 with primer and NanoChar can be applied to add fire and corrosion resistance. Alternative 2, being a truss, would be more challenging to fire and corrosion proof because of the amount of members, connections and small spaces. For this, Alternative 2 received a one. The second Alternative received a two for aesthetics. Although the MEP can be installed between the top and bottom chords, the truss would not be able to be colored because of fire and corrosion proofing. Alternative 2 could be delivered in pieces as discussed earlier and thus could be constructed directly off the trucks. Alternative 2, similar to Alternative 1 would require a smaller crane than the existing system. Alternative 2 has a weight of 200 tons which is about two thirds of Alternative 1. For this, Alternative 2 received a two.

Alternative 3 received a two for short term cost and a one for long term cost. Alternative 3 was the second most expensive alternative. Similar to Alternatives 1 and 2, Alternative 3 would have a higher insurance premium than concrete because it is made up of steel. Alternative 3, similar to Alternative 2 will also have a higher long-term maintenance cost because trusses have a larger surface area and more exposed connections. Similar to Alternative 1 and 2, the erection of structural steel would not have to be halted with Alternative 3. Alternative 3 would only take 5.5 weeks to install. For this, Alternative 3 received a three for schedule. As discussed for Alternative 1 and 2, Alternative 3 is made up of structural steel and would require annual maintenance for fireproofing/corrosion-proofing. The steel would have to be coasted in a material similar to Albi Clad 800 with primer or NanoChar to lengthen the systems life. Similar to Alternative 2, Alternative 3 also has many members making it more difficult to coat with proofing material. For this, Alternative 3 received a one. The third Alternative received a zero for aesthetics because it is not symmetrical: the quad (East) end of the truss must support the above floors. Similar to Alternatives 1 and 2, Alternative 3 receives a two for constructability because it could be delivered in pieces, constructed directly off the trucks, and would require a smaller crane than the existing system.

Table 20: Evaluation of Precast Arches and Three Steel Alternatives

Alternative Evaluation Decision Matrix				
Evaluation Criteria	Existing	Alternative 1	Alternative 2	Alternative 3
System	Precast Concrete Bents and Double T-Beams	Free Standing Steel Girder and Columns	Free Standing Steel Truss and Columns	Rigid Steel Truss and Columns
Cost				
Short Term	0	1	3	2
Long Term	3	2	1	1
Schedule	0	3	3	3
Maintenance	3	1	1	1
Aesthetics	3	1	2	0
Constructability	1	2	2	2
Total (out of a possible 18)	10	10	12	9

6.0 – Conclusions and Recommendations

The use of Building Information Modeling and information technology has the potential to change the face of the construction industry and facilities management. Applying this technology throughout the preconstruction, construction, and post-construction phases helps fill in the communication gaps between construction project teams and the Project's Owners; ultimately assisting with the management and lifecycle of the building. This project explored using BIM as a tool to provide continuity in the flow of information from the design and construction phases of the new Center to its occupation and operation by the Department of Facilities.

Theoretically at the beginning of the design process, constraints are defined by the function of the Project, the State's Building Code, and Owner. These constraints are imported into modeling software, such as Autodesk Revit and Navisworks, at which time specific materials and construction methods can be analyzed and evaluated. Building Information Modeling encompasses the capabilities of a structural analysis program, traditionally accomplished using such software as RISA. Once the method of construction is determined (i.e. using precast concrete arches or steel trusses), BIM is used for generating a preliminary 3D design that meets the criteria of the Designer. BIM facilitates the process of defining a structural configuration, proportioning the members, and presenting the resulting design to others. An example of the existing system is shown in Figure 38. For some projects, the Owner may request to have multiple alternatives of different prices or different appearances. In this case, it is easy for a designer to show the Owner what the alternatives will look like, as well as their estimated cost and schedule using BIM technology.

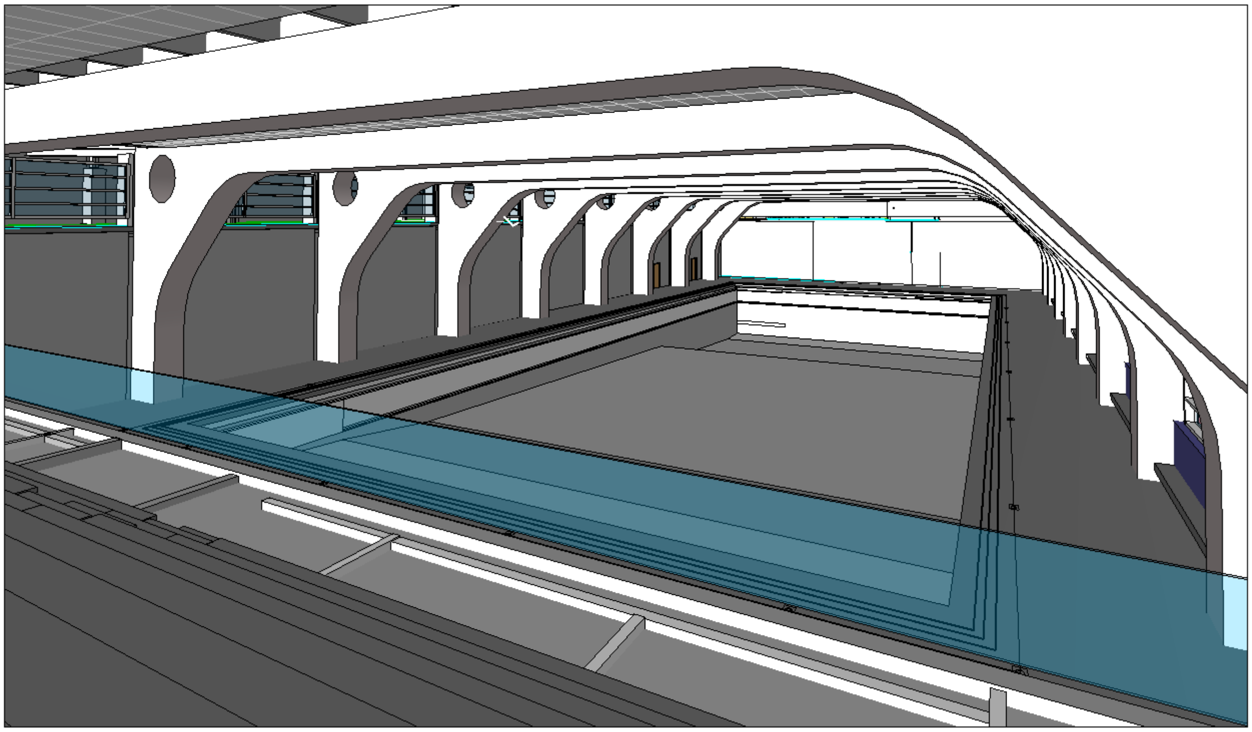

Figure 38: Existing Precast Arch Rendering (Courtesy of Cannon Revit Files)

For this project, however, the design of the alternatives was similar to that of the traditional process; based on the given constraints and the structural analysis using RISA, three steel alternatives were investigated and the completed design was imported into the Revit Model created by Cannon Design. The purpose of BIM for this portion of the project was specifically to demonstrate BIM as a visual aid for exploring alternatives. BIM provides a visual reference for those without a construction background who cannot easily decipher 2D plans.

The structural design process was extensive and technical. After the three alternatives were designed and analyzed, each alternative was evaluated based on a decision matrix that examined the cost, schedule, maintenance, constructability, and aesthetics of each alternative. The chosen steel design was Alternative 2, the free standing truss. Alternative 2 was the least expensive design yet still aesthetically pleasing. A 3D view of Alternative 2 replacing the precast arches of the new Center using Autodesk Revit Structures and Revit Architecture is presented in Figure 39.

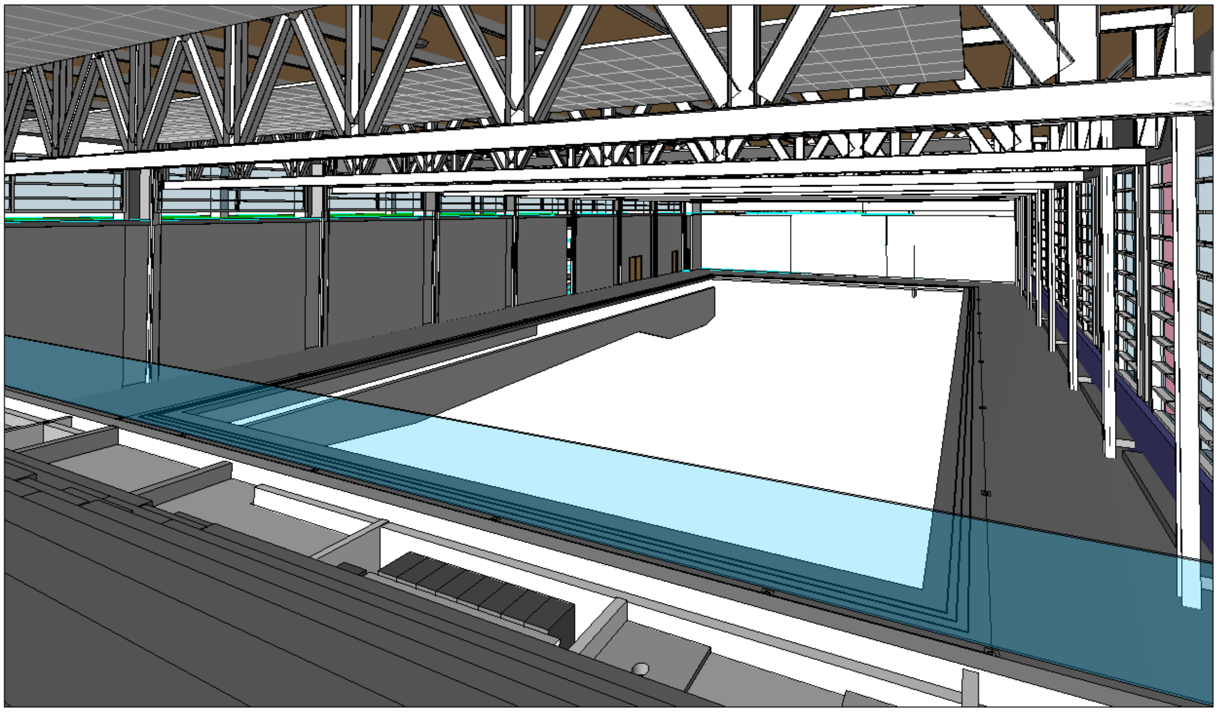

Figure 39: Free Standing Truss (Alt 2) Rendering

In exploring the development of a BIM prototype for the Department of Facilities, there was broad agreement by the members of Gilbane Construction and the Department of Facilities on the closeout information required about a door, a window, a piece of mechanical equipment, etc. This was a necessary step for the interoperability of systems applying intelligent BIM technology to their processes. The prototype was created using Autodesk Revit Structures, Revit Architecture, and the dimensions based on Cannon Design's drawings. Within the Revit Model, the *AHU Pool-Fitness 359* room was furnished with the MEP systems and equipment. These components were tagged with attributes (i.e. dimensions, capabilities, etc.) and linked to the computer's local file directory, which held digital versions of the O&M information and warranties that couldn't be displayed in the attributes menu.

Based on input by Department of Facilities, using BIM for its preventative maintenance and work order purposes would require a user-friendly interface and the ability to extract specific information about a hypothetical work order from the BIM. This report found it necessary to use the

Autodesk Design Review Software and the DWF file format, not only because it was free and easily obtainable, but also because of its simple user-interface and its compatibility with Microsoft Office and Asset Management software programs. The ability to present and share the information stored within the model permits the use of computer tools to assist in managing, using, and checking the accuracy of the data. The DWF Viewer gives anyone within the Department the ability to view the record BIM without requiring the Autodesk Revit software that created it.

The overall outlook on the implementation of BIM and information technology was positive, considering it has the potential to facilitate the maintenance and management of a building and provide a faster retrieval of information. Despite the slow transition from traditional paper libraries to information intelligent models, in a matter of time, facilities management will benefit from the increased accessibility, availability, and understanding of building information through the use of BIM.

Recommendations for Implementation

The management and maintenance of a building can be positively affected by storing the closeout documentation within the record BIM, thereby allowing the concepts of Asset Management and Preventative Maintenance to be applied by the Department of Facilities. The key to implementing the exchange of intelligent building information throughout a project requires a contractual agreement by the Owner and Construction Manager. This agreement must specify the components of the building; content required for each element, and the accuracy of the data objects that make up the record BIM.

This process permits developers of the record BIM, most likely the General Contractor, to create and publish a digital library of each system's closeout documentation into an organized file directory, and establish a link to the specific documents within the record model. A truly intelligent record BIM that represents the as-built conditions of the Project could be expected as one of the primary closeout items following the completion and final punch list of a Project

By no means does the requirement of a record BIM in the post-construction phase signify a complete substitution of paper. In the case of an emergency, such as a power outage, either paper documents or a laptop with the digital file directory stored on the computer's hard drive are vital to address the situation. However, emergencies aside, as the use of BIM becomes a requirement for construction projects, this tool will benefit the Owner years after the completion of a project by enhancing the Department's ability to maintain and efficiently use the building information that has been stored.

Recommendations for Future Work

The use of BIM in the design and post-construction phases is emerging from a new technology into a developed standard of the industry. The buildingSMART Alliance was established to address the overwhelming changes coming to the nation's construction industry. (BSA, 2010) This Alliance develops and promotes more efficient methods for gathering, storing, and sharing vital operation and maintenance information related to a buildings' lifecycle. (BSA, 2010) The Alliance currently promotes a common data schema that makes it possible to store and exchange relevant information between different software applications and more importantly different users. (BSA, 2010) The name of this data model is Industry Foundation Classes (IFC). IFC can be used to exchange and share BIM data as a new format, similar to the way Autodesk Design Review displays BIM data.

Construction Operations Building Information Exchange (COBie) is a rapidly evolving standard to capture information electronically during design and construction, to provide it to facilities managers. (Strelzoff, 2010) The COBie standard eliminates the current inefficient process of transferring massive amounts of paper closeout documents. Following the post-construction phase, the COBie document forms a live data set for continued use by facility managers to find, access, and update relevant maintenance documents. (Strelzoff, 2010)

These facts serve to show the importance of introducing BIM to Civil Engineering students at WPI. One of the most intriguing areas that was not within the scope of this research was that of using BIM throughout the design and analysis process for a structure. Similar in concept to a structural design MQP, a hypothetical building could be designed, analyzed, and then furnished with the MEP systems, fire protection requirements, etc. Perhaps, another independent project would integrate software and tools for the structural design and analysis, cost estimating, and scheduling.

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Appendices

Appendix A – Major Qualifying Project Proposal

Appendix B – Interview Questions and Responses

Appendix C – Structural Calculations and Product Data

Appendix D – Cost and Schedule Data

Appendix A – Major Qualifying Project Proposal

A MAJOR QUALIFYING PROJECT PROPOSAL
GFS 1102, LDA 1103

Enhancing Facilities Management and Structural Design through Building Information Modeling

Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
in Civil Engineering by

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Trevor Bertin

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Peter Schembri

Date: November 5, 2010
Approved:

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Prof. L. D. Albano

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Prof. G. S. Salazar

Abstract

Our project will investigate the potential of using Building Information Modeling (BIM) technology to improve Worcester Polytechnic Institute's Department of Facilities information system. The results of our investigation will be compiled into a white paper. Accompanying the paper will be an example prototype of a mechanical equipment room that demonstrates the use of BIM's capabilities on a facilities management application. Additionally, an alternative structural design for the precast concrete arches spanning the natatorium of WPI's new Sports and Recreational Center will be created accompanied by a construction schedule and cost estimate using BIM's 5D modeling. Information will be gathered through various types of research, including literature reviews, interviews and attending project meetings. The team will also collaborate with representatives of various companies associated with the new Center project, such as Gilbane Inc, Cardinal Construction and Cannon Design.

Capstone Design

The capstone design of the Major Qualifying Project consists of three main components. First is the analysis of the capabilities of BIM software and the investigation of its uses in facilities management. In parallel with this first component, an example of these capabilities will be developed using a mechanical equipment room as a prototype for the structure. Finally an alternative structural design will be developed to replace the precast concrete arches that support the ceiling in the natatorium with steel trusses. Some of the constraints associated with this project are economic, health and safety, sustainability, social, and manufacturability/constructability.

In order to complete the capstone design requirements for this Major Qualifying Project, the team conducted a limited exploration of how BIM software can be implemented into the design and the post-construction phases of WPI's new Sports and Recreation Center. Activities in the disciplines of construction management, structural engineering, and facilities management will explore standard pre-construction and post-construction tasks within the context of BIM. By exploring and implementing various aspects of BIM, our team seeks to provide insight into the potential benefits and limitations of BIM to the engineering and facilities management industry and from the results, provide a white paper, alternative steel design, and a BIM prototype of a mechanical room. Some of the constraints associated with this project are economic, health and safety, sustainability, social, and mechanical/constructability.

Economic:

Throughout the project the economic effects of construction will be taken into consideration. The planned truss design, including implications of fire protective materials and corrosion resistant materials, will be a major factor in the economic difference between the proposed and actual designs. Also taken into consideration will be the change from two contracts, concrete and steel, to one contract, steel alone.

Health and Safety:

An important factor in any project is the health and safety of its workers during construction. Hazards on site must be closely monitored and addressed to minimize risk. With the construction site located in close proximity of students, faculty, and staff, risks and hazards are elevated.

Sustainability:

This project will incorporate sustainability factors into both the facilities management deliverable and the alternative structural design. The BIM prototype will demonstrate how the software can aid the Department of Facilities in organizing important data to enhance the life cycle of the structure. The structural design will incorporate aspects required by LEED to be classified as a silver LEED structure.

Social:

The social implications of the construction process will also play a role in this project. With construction so close to the WPI quadrangle, an area of high student concentration, contact between the students and trades must be monitored. Also attending construction coordination meetings and owners meetings the project group will gain a real-world look into the construction process from two different angles, that of the owner and that of the construction manager.

Manufacturability/Constructability:

From a manufacturing and constructability standpoint, this project delves into the feasibility of using steel trusses as an alternative to the current precast concrete arches. The alternative design of the steel trusses consists of investigating the advantages and disadvantages of steel compared to precast concrete, determining the design loads that the trusses will support, selecting the appropriate dimensions for the members, and performing a structural analysis on the design. The procurement and erection of manufacturable trusses will also have aspects of economics and safety because the trusses require a suitable crane to lift the steel. If the current cranes on site do not meet these requirements then the cost of an appropriate and additional crane will become a factor.

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Chapter 1 – Introduction

The construction industry is a vital part of the economy of the United States, accounting for over 8 percent of the nation's gross domestic product. (Bogdan, 2000) The success of any construction project requires extensive communication among owners, architects, engineers, project managers and contractors. While each of the parties' duties varies greatly, an understanding of all aspects of the project is crucial for delivering a quality project on time and within budget. Throughout all phases of a project, failures in communication result in errors, unexpected and costly changes, delays in the schedule, and loss of vital information for the operation and maintenance of the completed building. Currently the construction industry finds itself in the middle of a technology revolution with the introduction of Building Information Modeling (BIM) software, but like any addition to an already functioning industry, BIM requires time in order to become a standard of the industry.

Building Information Modeling is a technological approach to storing and conveying coordinated, consistent, and computable information about the design and construction of a building, with the ability to visually display building components in a three-dimensional view. (Mendez, 2006) BIM's capabilities are enhanced by its parametric modeling engine, which "…interrelates building objects to other objects and coordinates the changes between them", which facilitates design decision-making, production of quality construction documents, prevention of structural conflicts, and prediction of cost estimating and construction schedule. (Rundell, R. and K. Stowe, 2005) While BIM is primarily defined as a modeling method, it is beginning to evolve into a communication bridge within the architectural, engineering, and construction industries: by initially using BIM throughout the duration of construction, the overall project can be completed faster with fewer delays, cost much less to the owner, and effectively store accurate operation and maintenance information for the owner.

Currently Worcester Polytechnic Institute (WPI) is constructing a new Sports and Recreation Center to meet its demand for a growing athletic community. The new 145,000-square foot Center provides a four-court 29,000 square-foot gymnasium, a natatorium with a 25-meter competition swimming pool, an 11,00 square-foot fitness space, a three-lane indoor jogging track, as well as rowing tanks, convertable racquetball and squash courts, dance studios, and offices for athletic personnel. With the new Sports and Recreation Center projected to open in the fall of 2012, all students, faculty, and staff will finally enjoy a facility that allows them to reach their highest athletic potential.

In order to fully ensure functionality of the built environment and deliver a project, which meets all of the Owner's specifications, WPI has asked the Project Manager, Gilbane Construction, to implement BIM within the construction of the new Center. While the implementation of BIM prior to the construction phase is usually the most desired, the use of BIM during any phase of construction is beneficial to the project. Currently the coordination meetings for the mechanical, electrical, and plumbing (MEP) areas are taking advantage of BIM to show in three-dimensions the structural clashes that exist between the trades on the two-dimensional drawings.

This project intends to explore the application of BIM to the pre-construction and post-construction phases of a building project. The question is how and to what degree can BIM make a difference in these phases to the Owner? Instead of the current practice of using BIM for its visual aid in coordination meetings during the construction phase, our project will explore its uses in the design of the project and the operations and management (O&M) storage of building information to the Owner. We expect to discover the potential benefits of BIM for WPI's Department of Facilities and for investigating design, cost, and schedule impacts of a possible alternative steel design for the precast concrete being used in the new Center. This will be accomplished through literary reviews, interviews, and attending the new Center's project meetings. As a result of our efforts, our team will create: a white paper that documents our uses of BIM for WPI, a BIM prototype of a mechanical room that displays the potential for information storage, and an alternative design for the precast/prestressed arches spanning the natatorium and its potential effects on the construction schedule and cost.

Chapter 2 – Background

This chapter of the report involves the non-technical information about the new Center that will help the project team gain a better, overall understanding of the design and construction planning of the new Center as well as information on facilities management and its potential capabilities with BIM. The planning and development of a project is key before conducting a technical review. Without this process unforeseen problems could arise that would be costly to address and delay the project. The chapter begins with an investigation of the new Center and its various components. Additionally the chapter covers BIM and related software. Lastly structural components are discussed.

2.1 Demand for a New Athletic Facility

Worcester Polytechnic Institute, founded in 1865, provides education to 3,453 undergraduate students and 1,153 graduate students, and brings employment to 365 faculty members. (WPI, 2010b) All members of the WPI community are encouraged to use the recreation facilities on campus, and currently there are two athletic facilities available to the entire WPI community.

Alumni Gymnasium, built in 1916, houses offices for faculty, locker rooms, a swimming pool, racquetball courts, and a 4,000 square foot fitness center. Harrington Auditorium, built in 1968, includes a 2,800 seat gymnasium used for sporting events, concerts and a small area for aerobic exercises. These two gymnasiums support 15 Varsity sports teams, 20 club sports, 10 intramural sports, and over 20 physical education classes. With the faculty and student body progressively increasing as well as the student participation in sports, the need for a larger sports facility has become a priority.

2.2 WPI Sports and Recreation Center

The original Master Plan for the new Sports and Recreation Center on the WPI campus was created in 2005. However, further planning and construction was delayed until the Spring of 2009 when Cannon Construction was brought on board as the designer of the project. Due to the economic crisis in 2008, it was realized that 2009 was not a viable starting point, and construction was again deferred. On October 30, 2009, the WPI Board of Trustees agreed to proceed with the construction of the Center starting in May just after the 2010 Commencement. The project is currently being financed through a combination of fundraising, donations, debt, and use of accumulated operating surpluses. (WPI, 2010c)

Figure 2: New Center from the WPI Quad

The 145,000 square-foot Sports and Recreation Center is currently being constructed at the west end of the campus quadrangle, adjacent to Alumni Field and Harrington Auditorium. A view of the facility from the quadrangle is rendered in Figure 1. The Center will provide space and equipment for activities which currently have little or no designated areas in the existing gymnasiums, such as rowing and robotics. A 16-person indoor rowing tank will be located on the ground level of the Center, along with a natatorium featuring a 25-meter competition swimming pool, a training and rehabilitation suite, and specialized spaces for racquetball and squash. This level, shown in Figure 2 will be directly accessible from Alumni field.(WPI, 2010a)

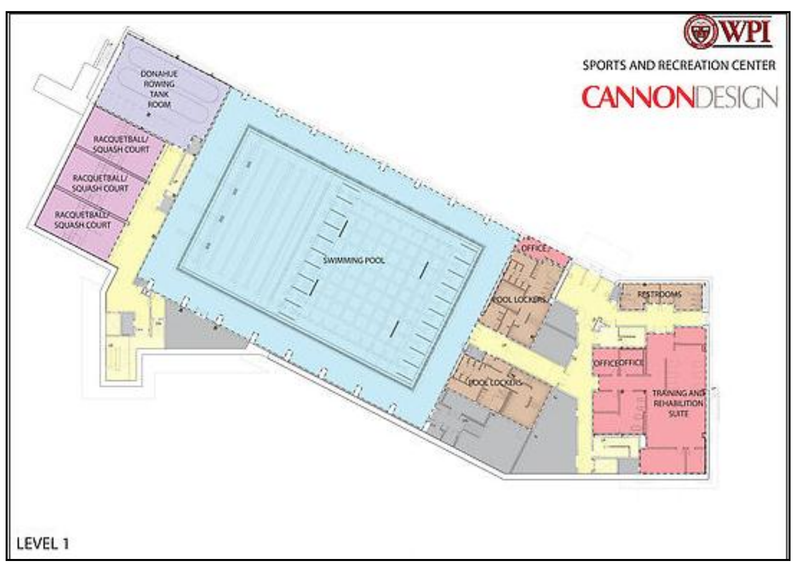

Figure 1: Ground Floor Plan

As a technology-based school, WPI holds several robotics competitions for their students and external organizations. Currently these competitions are held in Harrington Auditorium, yet there is limited space for the competitors to test, repair, and program their robots prior to competition. The new Recreation Center will house a robot pit on the 3^{rd} floor which will connect directly to Harrington Auditorium for competitions. The 3^{rd} floor, shown in Figure 3, will also contain spectator seating for the swimming pool, a conference room, and multiple offices for athletic department administrators and coaches. (WPI, 2010a)

The Center will be accessible from the campus quadrangle at the 4^{th} floor, shown in Figure 4. This level contains 12 more offices, a 29,000 square-foot gymnasium with four courts, locker rooms, and a fitness center. The fitness center expands to the 5^{th} level, supplying a total of 14,000 square feet of fitness space, more than tripling the current size of the fitness area in Alumni Gymnasium. The 5^{th} floor also contains meeting rooms, three multi-purpose rooms, and a suspended jogging track overlooking the gymnasium. The new Recreation

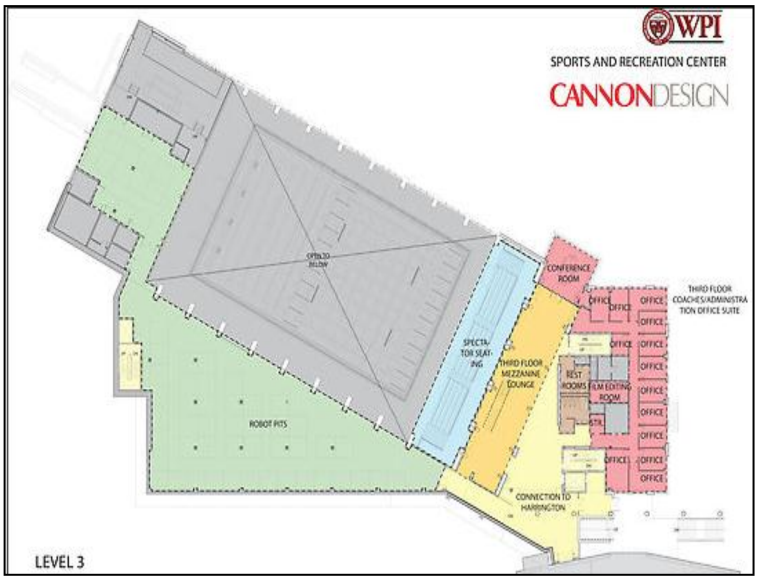

Figure 4: Level Three Floor Plan

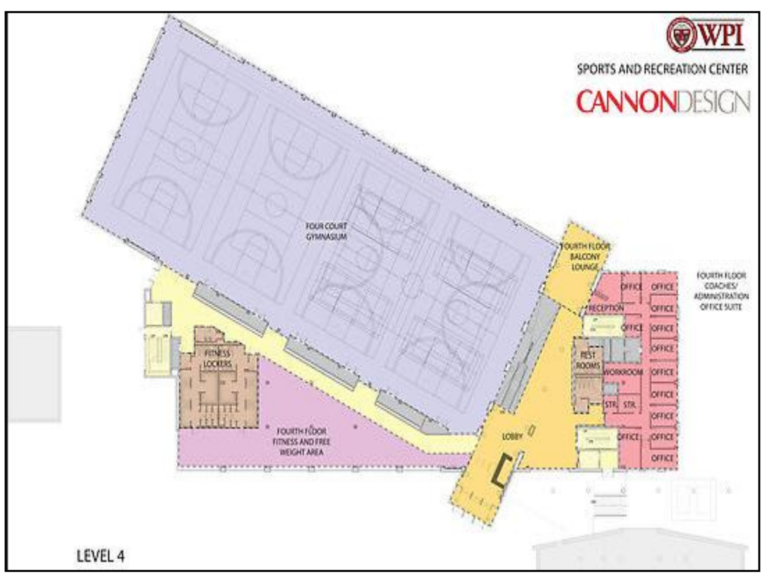

Figure 3: Level Four Floor Plan

Center will facilitate activities which currently take place in Alumni Gymnasium, including wrestling matches, indoor rowing, swimming, weight lifting, and racquetball. Subsequently, Alumni Gym will be converted for academic use. (WPI, 2010b)

2.3 LEED Certification

The new Center is being constructed with the goal of achieving Silver Leadership in Energy and Environmental Design (LEED) certification. There are currently two LEED-certified buildings on the WPI campus: East Hall and the Bartlett Center. (WPI, 2010c) LEED is a rating system started by the United States Green Building Council (USGBC) which encourages sustainable design, construction, operations and maintenance solutions in buildings and communities. Additionally, it establishes protocols and procedures for owners to maintain during construction and occupancy. (U.S. Green Building Council, 2010)

LEED uses a point system to designate different levels of sustainability. Points are grouped into five categories. Upon completion of a building that is ready to be inspected, a team of LEED Accredited Professionals will determine the point total based on construction procedures, current equipment, and future building protocol. (U.S. Green Building Council, 2010) The sum of these point totals determines the facility's sustainability level. Table 1 shows the LEED categories and possible point totals for schools.

Table 1: LEED Point System for Schools (U.S. Green Building Council, 2010)

LEED® for Schools

Total Possible Points**	110*
Sustainable Sites	24
Water Efficiency	11
Energy & Atmosphere	33
Materials & Resources	13
Indoor Environmental Quality	19

*Out of a possible 100 points + 10 bonus points

**Certified 40+ points, Silver 50+ points, Gold 60+ points, Platinum 80+ points

Innovation in Design	6
Regional Priority	4

The new Center will have to obtain 50+ points out of the five categories to achieve Silver certification. The Sustainable Site category awards points for promoting responsible, innovative and practical site design that are conscious of the flora, fauna and water & air quality. The Water Efficiency category grants points for minimal drinking water consumed in the building. The Energy and Atmosphere category promotes the practices of tracking building energy performance, managing refrigerants and using renewable energy. The Materials and Resources category strives to minimize waste while the building is being built and after its construction. The Indoor Environmental Quality category points are awarded for indoor environmental and air quality control as well as thermal comfort. Bonus points are granted for innovative designs that minimize local environmental concerns. (U.S. Green Building Council, 2010)(Mendez, 2006)

In order to achieve the Silver LEED certification, the Center will utilize 50 solar thermal panels on the roof in order to help heat the pool area. Compared to conventional pool heating, the solar panels are expected to save more than $50,000 in operating costs and reduce carbon dioxide emissions by 4,400 pounds per year. The Center will also contain underground storage tanks that will collect 50,000 gallons of rainwater from the roof, ultimately reducing the building's water consumption by more than 800,000 gallons per year. Also, more than 75% of the construction waste will be recycled and diverted from landfills.

2.4 Project Management

Project Management can be simply defined as "The art and science of coordinating people, equipment, materials, money and schedules to complete a specified project on time and within approved cost."(Oberlander, 1993) A Construction Manager (CM) must lead a project team through the rigors of the construction process mainly through the facilitation of five basic functions: planning, organizing, staffing, directing and controlling. (Oberlander, 1993) The CM of a project must devise a course of action that will guide the project to completion, within the restraints of cost and time. Incorporated in this plan is the organization of personnel, materials, equipment and schedules. The CM also takes on the responsibility of staffing the job, hiring subcontractors and construction specialists based on the needs of the project. By closely directing the job, a CM has the ability to ensure the overall plan is being adhered to and the schedule of the project is being maintained. Finally the CM must be controlling, constantly gathering information to establish a means of measuring the scope of a project and predict possible deviations to the plan and schedule.

CM-at-risk is one type of contract agreement a Construction Management firm may have with the owner of the project. This is the type of contract WPI has chosen to construct the new Center. Through this relationship, a CM operates as a consultant to the owner during the preconstruction phase, and then takes on the role of the project supervisor throughout construction. During preconstruction a CM offers professional management assistance, mainly scheduling, budgeting, and constructability advice. Once the construction phase begins, the CM is then responsible for subletting construction work to subcontractors and guaranteeing the completion of a project on schedule and, for this project, within a Guaranteed Maximum Price (GMP). This delivery method associates risks of the project onto the project manager. These risks include a cost overrun where the project cost ends up exceeding the GMP, which can cost the CM a great deal of money. Since the CM will have to cover the difference between the actual cost and the GMP. The CM is also responsible for any defects to the building and for providing a quality finished product. This holds true even years down the road, which can cost the CM long after the project is completed, in some cases. (Strang, 2002)

2.4.1 Cost and Scheduling

Cost estimation is a pivotal function that a Construction Management firm must perform, and possibly the most difficult. Taking into consideration the scale of the project; the cost of materials, labor and equipment; the schedule and potential implications during construction, a series of approximations are made to formulate a fairly accurate representation of the cost of the project. Two types of estimates are generally made to grasp the cost of the project. Approximate estimates, or budget estimates, are used during the preliminary stages of the project, mainly the feasibility study and initial design phases. Detailed estimates, or contractor's estimates, involve more precise calculations and are used by the construction manager to bid the project, or to determine how much the owner must pay to complete the project. (Oberlander, 1993)

There are two types of costs accounted for in an estimate. Direct and Indirect costs are combined to produce a total estimated cost for the project. Direct costs include all subcontractor construction and design costs, material, major equipment, and labor. Indirect costs include all insurances, bonds, permits, minor equipment, mark ups, and overhead costs. For the Center three estimates were developed, created indually by Gilbane, Cannon Design, and Cardinal Construction. Upon completion the three estimates were consolidated creating asingle more accurate estimate.

The schedule lays out a series of steps towards the completion of a structure which is essential to the organization of a construction project. A well thought out and detailed schedule is a very effective tool for preventing problems during construction. However this is a complex task that includes all aspects of the project. Incorporated in the schedule are the procurement and delivery of materials to the job, coordination of labor and equipment, and interface of the work of all sub-contractors while still allowing contingent time for changes to the design and construction process.

2.4.2 Project Organization

Assuming the role of Construction manager for the new Center is Gilbane Inc. Based out of Providence, Rhode Island, Gilbane Inc. is one of the largest privately family-owned companies in the construction and real estate industry. Founded in 1873, Gilbane has taken part in many notable projects. These projects include the Smithsonian Institutes National Air and Space Museum, the Vietnam and World War II Memorials, and the Winter Olympic Venues in Lake Placid, NY. Gilbane has also undertaken many projects that are close to home, such as WPI's Bartlett Center and East Residence Hall. Staffing Gilbane's work force for the project are William Kearney (Project Executive), Neil Benner (Project Manager), Justin Gonsalves and Melissa Hinton (Professional Engineers) and Frank Danahey (Field Supervisor).

Cannon Construction, established in 1945, is the design firm for the new Center. They have undertaken the design of the project and submitted the final plans to WPI. Heading the project for Cannon is the Contract Administrator, Dominic Vecchione. Mr. Vecchione manages the design process as well as addresses any alterations to the design throughout the construction process.

The Owner's Project Manager (OPM) for the new Center is Cardinal Construction. WPI has a long history with Cardinal on various projects, such as the Life Science Building, East Residence Hall and Goddard Hall, and once again turned to Cardinal for their services. On staff for Cardinal are Brent Arthaud and Michael Andrews as the leading Owner's Project Managers. The role of an OPM is to lighten the load of the owner, enabling them to attend to their everyday responsibilities throughout the construction process. An OPM also provides services including financial and constructability insight. Figure 5 shows the hierarchy of the WPI representatives involved in the project.

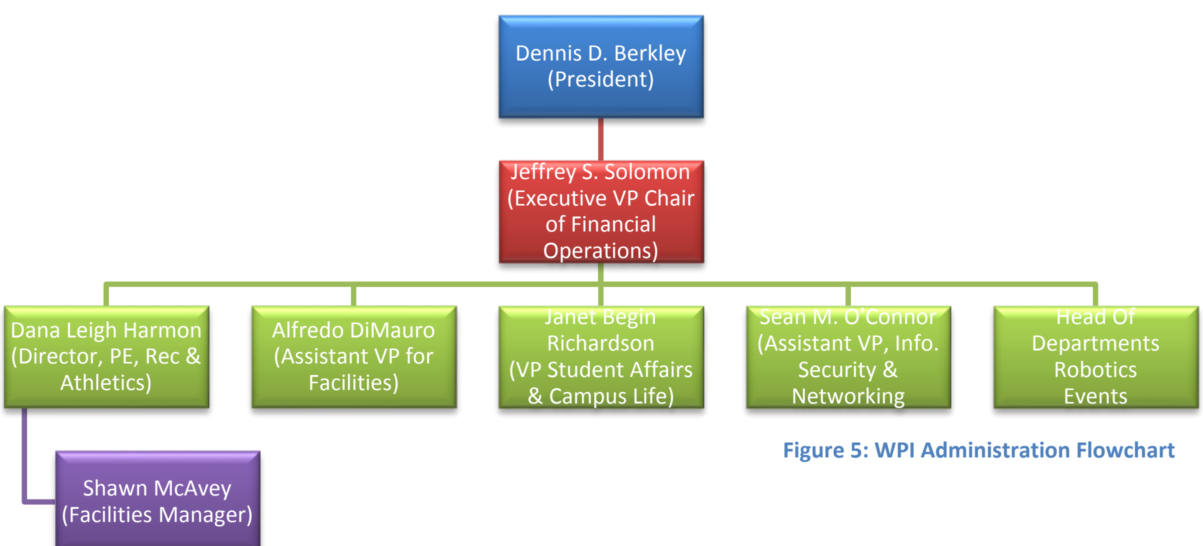

Figure 5: WPI Administration Flowchart

A flow chart of the main parties involved is displayed in Figure 6, which shows the external organizations (Gilbane, Cannon, and Cardinal).

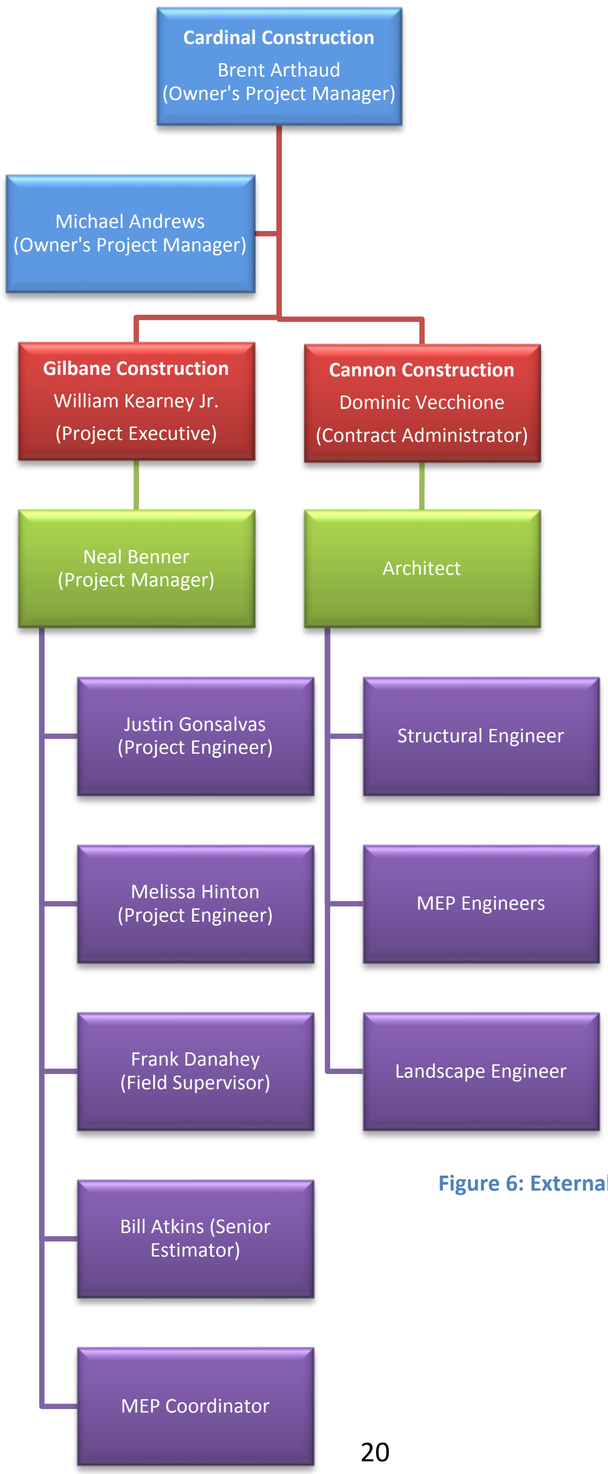

Figure 6: External Organization Flowchart

2.5 Expected Challenges

With any construction job, there are challenges that arise due to complicated mechanical systems, existing site conditions, constructability implications, irregular designs, and design errors or omissions. During the design phase, the Recreation Center had encountered challenges concerning the existing soil properties and the stability of the adjacent buildings. In order to support the soil configuration at Harrington Auditorium and Morgan Hall during excavation, soil nailing and micropiling techniques were used. (Benner, 2010) These are common techniques used with soft soil since they increase its apparent bearing capacity by transferring loads and stresses from the soil to the nails and piles. Harrington Auditorium posed more of a problem than Morgan Hall because the Recreation Center foundation is deeper than that of Harrington, and therefore the micropiling process had to be extensively engineered to avoid undermining the stability of the existing foundation.

Another challenge expected is the coordination, integration, operation, and maintenance of the mechanical, electrical, and plumbing (MEP) equipment. For example, the large pool area requires a complicated ventilation system to ensure proper air quality within the natatorium. Subsequently, many pipes and ducts will be located in tight spaces within the ceiling. It is important to arrange the MEP pipes and equipment in such a way that there are no spatial interferences or clashes with other MEP equipment or any structural components of the building. In order to prevent these clashes, Gilbane uses a computer program called Navisworks, which is discussed in detail in section 2.11 of the Background. The use of Navisworks in this project is supplementary to the traditional 3D MEP coordination process that takes place.

2.6 Building Operations and Maintenance

On a college campus, buildings provide the students and faculty a healthy, active, and educational environment. In order to make this happen, facilities management is generally concerned with the life cycle of the buildings as well as their energy efficiency so that the interior environments are comfortable and healthy. The life cycle of a building refers to the view of a building over the course of its entire life – in other words, viewing it not just as an operational building, but also taking into account the design, installation, commissioning, operation and decommissioning phases. Energy efficiency is not so easily defined – its issue being that the topic is relatively ambiguous. (Mendez, 2006) According to an M.S. Thesis written by Ronald Mendez, "The perpetual issue for managers has been the cost of supplies and services, and not about standards because no laws setting such limits have been established."

The United States Department of Energy (DOE) states that, addressing operations and maintenance with a predictive maintenance approach will detect the onset of equipment degradation and to address the problems as they are identified. This approach allows casual stressors to be eliminated or controlled prior to any significant deterioration in the physical state of the facility. (U.S. Department of Energy, 2007) Ultimately this method leads to more functional capabilities of a facility. In creating an effective Operation & Maintenance (O&M) program, the Department of Energy recommends that the following procedures be considered (U.S. Department of Energy, 2007):

- Ensure that up-to-date operational procedures and manuals are available
- Obtain up-to-date documentation on all building systems, including systems drawings
- Implement predictive maintenance programs complete with maintenance schedules and records of all maintenance performed for all building equipment and systems
- Create a well-trained maintenance staff and offer professional development and training opportunities for each staff member

- Implement a monitoring program that tracks and documents building systems performance to identify and diagnose potential problems and track the effectiveness of the O&M program. Include cost and performance tracking in this analysis.

In order to assure the environment that a college campus wishes to provide for its community, a predictive maintenance approach would likely be considered. The DOE's recommendation list, while thorough, provides a struggle for facilities managers and their staff when implementing a program that looks to complete all of these tasks for its buildings.

2.7 Facilities Management

The mission of the WPI Department of Facilities is "to provide a safe, clean, properly maintained environment for the WPI community," in support of its academic, athletic, and social activities. (WPI Facilities, 2010) The Department of Facilities is responsible for maintaining all the physical components of the buildings owned and operated by WPI. This includes mechanical systems, heating and air conditioning systems, fire suppression and detection systems, emergency/security systems, electrical, plumbing, building envelope and lock systems. The Department's purpose is to "broadly oversee the Institute's physical assets" and more specifically, "to maintain the adequacy and condition of capitol assets, to develop and periodically review policies, to advocate for new structures and rehabilitate or remove older structures, and to make certain that adequate levels of funding exist for facilities maintenance and operations."(WPI Facilities & Campus Committee, 2010) However, the areas of most concern are the MEP and HVAC systems, as these are more prone to needing routine maintenance. Another item of concern is the consistency of building components. The desirability of a facilities department would include common building components, such as lighting fixtures, among the campus buildings for the purpose of reducing inventory costs and having a consistent system. The Department of Facilities is directed by Alfredo DiMauro and then organized into multiple divisions, such as Customer Service Center, Building Projects & Renovations, and custodial and technical trades (See Figure 7).

Figure 7: Department of Facilities Organizational Chart

2.7.1 Close-Out Documents in Facilities Management

The MEP systems will require much attention during construction as well as post-construction by the WPI facilities management. The complicated systems will need to be maintained properly by WPI in order to run efficiently for years to come. In order to help owners manage their new buildings, close-out documentation is provided to the owner for their reference and use in the future at the end of the project. A list of the documentation Gilbane must provide to WPI can be found in the Close Out Procedures located in the Project Specifications. The required documentation includes but is not limited to inspections, warranties, final cleaning, operation and maintenance data, and record drawings

(Cannon Design, 2010). Record drawings, also known as “as-builts”, are a revised set of drawings created by the contractor or subcontractors which reflect all changes made to the contract drawings throughout the construction process. They show exact dimensions, geometry, and locations of all elements of the work completed under the contract. (Business Dictionary, 2010)

With current two-dimensional (2D) as-built drawings, necessary maintenance information about equipment or material is not easily accessible. Necessary information includes operational instructions for equipment, maintenance guidelines, warrantee information, testing schedules, and manufacturer information. Each piece of equipment installed in the new Center will have this information accompanying it, which is important for the operations of facilities management. An example of equipment vital to the lifecycle of the building would be the generator located on the rooftop. Facilities management would need to know not only the information shown in the as-built drawings, but would also need to incorporate the other close-out documentation listed above which is received separately from the as-built drawings.

The incorporation of O&M information and other close-out information in 3-D as-built drawings is a feasible concept, however has yet to be implemented by WPI’s Department of Facilities. Building Information Modeling, or BIM, has made this process possible through its ability to attach attributes to physical components. BIM utilizes computer software to create a three-dimensional (3D) model of a project, which includes the MEP systems, structural and architectural elements, and almost everything in between. It also can store information about each element placed in the model. A further description of BIM’s functions and capabilities is described in Sections 2.10 and 2.12.

2.8 Computer Aided Design

Computer Aided Design, or CAD, is a tool that was developed to take the place of work generally done on pencil and paper. This system facilitates the design process through a variety of innovations that CAD brings to its field. In the absence of CAD, an architect designs a rendering of a model to suit the needs of the owner. Once the design is completed the structural engineer begins to define the structural components to support the building. Simultaneously, the mechanical engineer designs the inner workings of the mechanical, electrical, and plumbing within the structure. Throughout this process there is very little collaboration between the engineering parties to mitigate possible conflicts in design and physical conflicts in construction. Upon completion of design the contractor or project manager is given a set of plans that have been merged together in order to complete the structure. Discrepancies which arise between the designs would be sorted and solved in the field typically with approved yet improvised solutions.

CAD, on the other hand allows architects and engineers an easier means to consult one another in the design process. Rather than discussing solutions over extensive printouts being made and mailed to another party to decipher, a file can be conveniently placed on a flash drive containing all of the relevant information. CAD also allows these 2D plans to be converted into 3D objects. This feature provides a significant advantage because it allows individuals who do not have a structural background to physically see the project being designed. CAD's features, such as layers, drawing sheets, schedules, graphic symbols, notation, and plotting capabilities take the design process from a simple drawing to a model that can contain vast amounts of information relevant to the construction of a structure.

2.9 Autodesk Revit

As designs evolve from two-dimensional plan drawings into three-dimensional models, a high level of effort is required by designers to manage and coordinate these CAD systems. Autodesk Revit software helps architects and designers gain a competitive advantage with tools that enable one to design freely, keep information well-coordinated, and deliver a finished product more efficiently. Revit is widely-used software due to its parametric modeling, which has been noted as its greatest asset.

(Khemlani, 2004) In a conventional CAD application, an architect draws walls, windows, or doors with a multitude of steps; first drawing lines, creating a "block" to be saved within the CAD software, and then accessing the "block" later in the drawing and placing it in its assigned locations.   With parametric modeling, all updates to a particular designed "block" are updated automatically, which keeps the user from going through the tedious process of updating each element manually throughout the design.   Parametric modeling ensures that all drawing components and views are always consistent.(Autodesk, 2010)

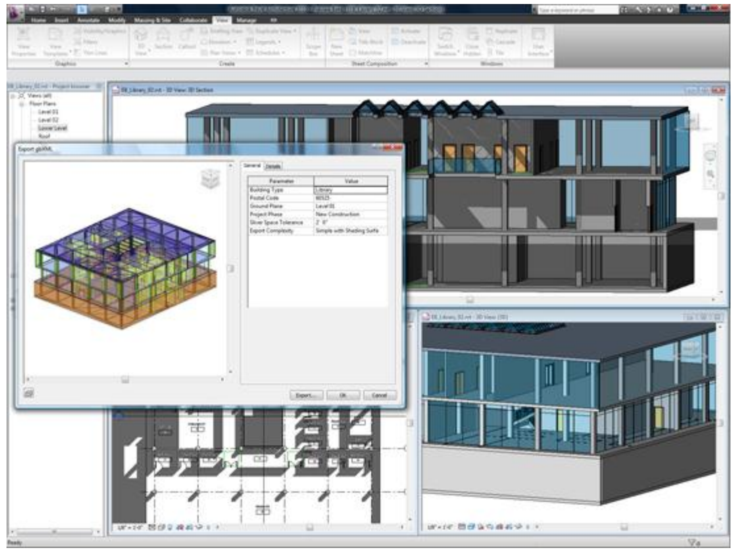

Figure 8: Autodesk Revit 3D Model

In addition to the building components, Revit supports integrating the physical site and elevations into the building model, thus displaying real world information about the project and where/how it sits on the project site.   Figure 7 shows an example of a structure encapsulated in Autodesk Revit. (Autodesk, 2010)

Autodesk Revit MEP is another product which minimizes coordination errors between MEP systems, architectural designs and structural elements.   For example, the coordination of Revit and Revit MEP would prevent a duct from being designed to go through a structural beam, by importing the two systems together. (Autodesk, 2010)

Using conventional CAD-based Revit products, like Revit: MEP and others, engineers and designers visualize the 3D design and transfer it to a drafted representation. These designs, which are generated by each scope, are not computable with each other – the elements and systems within do not know how to interact with each other. Building Information Modeling captures these functional relationships between building elements and systems. Building components, such as walls, beams, mechanical ducts, and pipes all "know each other" and how to react with each other to create a building.

2.10 BIM

Building Information Modeling, or BIM, is a relatively new term in the construction fields. First coined by Autodesk in 2002, BIM is an innovative approach to enhance the design and construction process. BIM is a representation of a building as an integrated database of information incorporated into the model of a structure. (Eastman, Teicholz, Sacks, & Liston, 2008) A BIM model takes all the information that is usually found in separate files and integrates them into an all encompassing master file. BIM can also be adapted for post construction purposes, giving way for various uses in facilities management.

BIM enhances the design and construction experience by enriching the process. Tasks that were once done individually can now be brought together to form a simulation of the building and its components. Incorporation of information such as material quantities, installation dates, subcontractor responsibilities, alternative materials, site-management and equipment coordination are now integrated within the model to produce an all-encompassing database. BIM provides a means for visualizing alternative designs and proposals for consideration along with addressing "what if" scenarios, prior to experiencing them in the field. Facilitation of cost estimation is another advantage to the BIM process. Material quantities and properties can be extracted from the model and analyzed to ensure accurate estimates. This allows the estimated cost to stay relatively updated with changes to the model and materials. By showing the estimated cost at a specific time along with the construction progress at that time, a 5-dimensional (5D) model is created. This model generates a visual representation to the owner and the project team, allowing them to see all components of a building in respect to cost, schedule, and the 3D building constituents.

2.11 Navisworks

The Autodesk Navisworks product delivers a project review software for the 3D coordination, 4D planning, photorealistic visualization, and accurate analysis of an entire project. Navisworks creates a whole-project model by integrating the various designs defined within all Autodesk Systems into a complex building information model. With Autodesk Navisworks software a user can collaborate, coordinate, and communicate more effectively to reduce problems during design and construction. One of its features that is being used in the new Center is its clash detection software, which anticipates and avoids potential problems before construction. Clash detection allows the Center's project team to track the status of clashes as they are found and resolved, export reports with results of clash tests, and include comments and screenshots to communicate issues to the project team. Figure 8 illustrates how Navisworks detects and communicates that a pipe interferes with a structural component by highlighting the clash. (Autodesk, 2010)

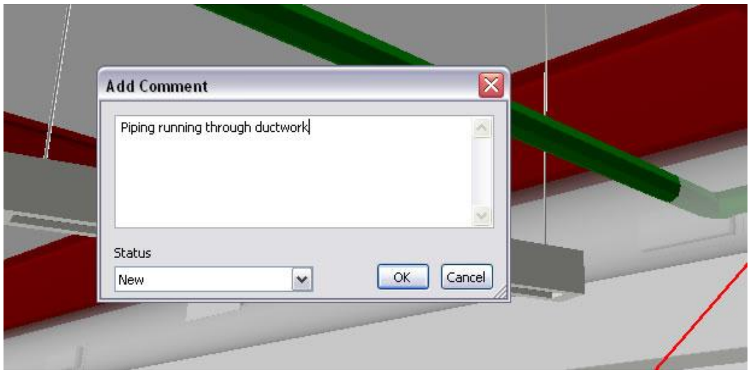

Figure 9: Navisworks Clash Detection {{32 Autodesk 2010}}

2.12 Case Studies

In this section we present three case studies of projects in which BIM played a significant role. They represent the experiences of owners, architects and engineers – all pioneers in the application of BIM. Taken as a whole, the case studies cover the use of BIM across all phases of the construction process by a wide range of participants. Each case study demonstrates a varied set of benefits to various organizations, resulting from the implementation of BIM processes and tools. Neither project has yet realized all nor even a majority of BIM's potential benefits, and it is doubtful that all of the benefits that the technology enables have been discovered or even identified. The three case studies present aspects of the BIM process and focus on the ways each team used the available tools to maximize their benefit.

2.12.1 Autodesk Revit: Implementation in Practice

Lachmi Khemlani, a Ph.D. professor in Architecture from University of California Berkeley, conducted a detailed research study to investigate how "Autodesk's premier BIM tool," Revit, was being implemented in architectural practice. (Khemlani, 2004) The intent of this case study was to provide detailed information on how Autodesk Revit is currently being implemented to investigate the measurable return of investment (ROI) data collected from Revit users and reveal some key insights into the successful deployment of Revit and BIM. Dr. Khemlani was interested in determining the key strengths and identifying the challenges involved in implementing Revit, and gauging the impacts of the software on the firms involved in the study. The study was performed by conducting surveys of several architectural firms that were in various stages of deploying and evaluating Revit.

Autodesk, consulted by Khemlani, conducted a web survey in November 2003 seeking information about how firms have implemented and are using Revit, with the intent to investigate its ROI. Over a hundred responses were received, and most of the firms expressed a strong liking for Revit and respect for its capabilities, in spite of some challenges during implementation. Some firms found Revit easy to learn and use, while others described the learning curve as steep, even for tech-savvy users. One respondent described Revit as "the first car compared to the first horse" and having experienced the speed, efficiency, and effectiveness of the car ride, none of these users want to go back to using the horse despite its, ease and familiarity. Overall more than half of the survey respondents strongly agreed (on a scale of 1 to 5 the average was a 4.22, with 5 denoting strong agreement with the statement) that Revit has helped their firm increase the level of service, quality, and performance that they are able to provide to their clients. (Khemlani, 2004)

The research study did not yield much evidence on the deployment of Revit on business practices; however, a 300-person firm, who felt like they were very advanced in their Revit implementation, reported that "they had only used half the number of staff that had been originally budgeted and completed the work twice as fast." The web survey also yielded some formal measurements that can be used to determine ROI: after an average productivity loss of 25-50% during the initial training period on Revit, it took most respondents 3-4 months to achieve the same level of productivity using Revit as with the previous design tool. Firms further along the implementation process found several benefits, none of which can be quantified: more time for design; better understanding of design; better presentation of design concepts to clients; no fear of making last-minute changes; better documentation with less errors; less tedium; more confidence in taking on projects; lesser divide between the designer and the "CAD person"; and so on. (Khemlani, 2004)

The most appreciable impact of Revit implementation on business practices, in terms of profitability, was felt by one firm that does work where information management is critical rather than the traditional architectural design work. This firm specializes in facilities management and found that the ability to derive and deliver accurate and coordinated drawings, spreadsheets, and 3D views from the same set of information had a major impact in extending their abilities as a manager.

2.12.2 United States Coast Guard BIM Implementation

The United States Coast Guard (USGC) plans, designs, builds, and manages a variety of 8,000 owned or leased buildings and nationwide land holdings. For any given project, the USGC may be the owner, tenant, or design team. The USGC continually assesses the condition of existing facilities, their mission dependency, and current space utilization. These evaluations of their facilities are used to analyze planning, including but not limited to renovations, facilities maintenance, or new construction. For the USCG, their types of operations were ripe for the advantages of using the intelligence of BIM to optimize data entry, knowledge capture, and data reporting compared to outdated traditional methods.(Eastman et al., 2008)

In order to begin the implementation of BIM, the USCG needed the most up-to-date 2D as-built drawings, an ArchiCAD building model, assessment data from consulting teams, and new date to be updated within ArchiCAD. Of these requirements necessary for BIM implementation, USCG found the most crucial information to be the as-built drawings. Updates to the BIM database were made using formatted spreadsheets through Microsoft Excel, which was chosen for its ability to keep data conformed to set standards as well as forcing consistency among entry.(Eastman et al., 2008)

The USCG found the simplicity and ease of entering assessment data within the model to be a great and helpful asset. For example, capturing knowledge about hazardous materials is critical to each assessment. The USCG team in the field would record the types of hazards (lead paint, asbestos, etc.), the degree of its condition, its quantity, location, height above finished floor, and other helpful data points directly in the model. With this information, the team created a new hazard object that was added to the model and the entered object parameters and important information about the hazard via pull-down menus.(Eastman et al., 2008)

2.12.3 The Building Information Model in Facilities Management

In an M.S. thesis written by WPI graduate student, Ronald Mendez, the benefits of BIM to the design, construction, and closeout phases of a project were investigated to address the current communication gaps between the parties involved in the project. Most importantly, the study examined the transfer of information and documents between the construction manager and the owner at the project's completion. This valuable information, consisting of as-built drawings, O&M manuals, warranties and other documents, is generated throughout the length of the project. It sometimes goes unrecorded and is not thoroughly understood by the owner at completion. (Mendez, 2006)

The intent of Mendez's research was "to explore how BIM could be used to improve the continuity in the flow of information in a coordinated and comprehensive manner from the design and construction of the building to its occupation and operation by the owner."(Mendez, 2006) In order to explore the possibilities of BIM, Mendez used literature reviews, case studies, interviews with WPI's Department of Facilities and a survey of universities in the Worcester area who've had recent construction on their campus. In addition to the research conducted with staff from WPI's Department of Facilities, the survey with the four Worcester universities focused on what was demanded or requested when the newly constructed building had been handed over by builder and if this information was satisfactory.

Mendez's study found that the use of BIM and information technology has the potential to change the face of the construction industry by bridging the gaps in communications between the architects, engineers, contractors, operators, and owners. (Mendez, 2006) While there was an initial loss when implementing BIM into an existing program, the design time was found to be reduced by 40%. Mendez discovered that construction could also be enhanced and shortened because of the visual aid to plan and coordinate tasks in meetings. In the post-construction phase, the closeout process can be changed by having accurate information made easily accessible to the owner if BIM has been used throughout the project.

The limitations of BIM were found to be substantial because implementation of this technology requires not only a change in the design and construction phases, but also in the way information is managed post-construction. Two of the four Worcester universities that were contacted were optimistic about the possible improvements to their facilities management through information technology. The remaining universities believed that information technology would be helpful but its benefits were outweighed by the cost in terms of time, money, and personnel training.(Mendez, 2006)

Another limitation was the construction industry's reliance on paper documents and as-builts, which is influenced by not needing or wanting to have to learn how to use the software. Most importantly, Mendez found that accessibility was another obstacle that BIM implementation would have to hurdle. Not only would utilizing BIM in project meetings require a large high definition monitor to display the graphics, but it would also require a machine capable of supporting the software's system requirements.

Mendez argues that BIM will become widely used among facilities managers and operators in the same manner that Word and Excel are commonly used programs. In addition, the Internet was found to be a great medium to present BIM and share its various components within the Department of Facilities, as long as security concerns were addressed to protect the access of vital building information.

2.13 Structural Components

Two major structural materials being used in the new Center, steel and concrete are discussed in this section. Each material has significant advantages and disadvantages. Of particular interest are the precast concrete arches spanning the natatorium. These arches represent the only concrete used in the building, besides the foundation.

2.13.1 Steel

The new Center is being primarily constructed out of structural steel. Structural steel is a versatile material that can be used in many situations. Steel is very reasonable when its great strength, light weight, ease of fabrication, and many other desirable properties are considered. The advantages and disadvantages of steel are represented in Table 2. (Durham, 2008; Eustache, 2006; McCormac, 2008)

Table 2: Steel Characteristics

Steel-In General			
Advantages		Disadvantages	
Properties	*Description*	*Properties*	*Description*
Cost	-Low cost per square foot	Durability	-Less durable than concrete with natural disasters and equipment
Design Flexibility	-Spans over 100 ft are not uncommon; makes remodeling easy -Few columns necessary	Corrosion	-Susceptible to corrosion when freely exposed to air and water -Must be painted frequently to prevent corrosion
High Strength	-High strength of steel per unit weight	Fireproofing Costs	-Strength reduced tremendously at temperatures commonly reached in fires -Excellent heat conductor -Need to be protected by materials with insulating characteristics & sprinkler systems
Uniformity	-Properties of steel do not change significantly over time	Susceptibility to Buckling	-As length and slenderness increase of a compression member, danger of buckling increases
Elasticity	-Steel behaves close to design assumptions	Fatigue	-Strength reduced when steel is subjected to stress reversals or variations of tensile stress
Permanence	-Steel frames properly maintained will last indefinitely	Brittle Fracture	-Steel may lose ductility and become brittle at high stress concentrations
Ductility	-Can withstand extensive deformation without failure under high tensile strength -Prevents premature failures -Visual evidence of impending failure		
Toughness	-High yield strength -Can be loaded and deformed without affecting overall integrity		
Constructability	-Fastened together by simple connections -Fast erection		
Reuse/Recycle	-Material can be reused after disassembly -Has scrap value		

2.13.2 Concrete

The new Center will have precast/pre-stressed concrete arches and double tee beams spanning over the natatorium. A rendering of the arches over the pool area is shown in Figure 9. Precast/Pre-stressed construction is useful because of its ease of constructability and its resistance to wear along with many other attributes. Precast concrete is concrete cured into a specific shape at an offsite location prior to installation. Concrete is poured into forms, made typically of wood or steel, and left to set for 12 to 24 hours after which it is removed. These pieces are then shipped to the construction site and erected. Precast components are reinforced with either reinforcing bars, high tensile strength steel strands, or both. The strands are pre-tensioned and secured in the forms before concrete is poured. After the concrete cures, the strands are cut creating a compressive force applied to the concrete. This is known as pre-stressed concrete.

Figure 10: Precast/Pre-stressed Arches in Natatorium {{15 WPI 2010}}

Table 3: Pre-Stressed Concrete Characteristics

Pre-Stressed Concrete – In General			
Advantages		Disadvantages	
Properties	*Description*	*Properties*	*Description*
Reinforced	-Same as conventional reinforced concrete	**Cost**	-More expensive then reinforced concrete
Cracks	-No cracks at working loads -Wires/bars create compression before loading	**Design**	-More complicated
Durability	-With removal of cracks it becomes better than reinforced in durability -Allows use of high tensile steel		
Efficient	-Smaller members carry same loads		

Pre-stressing overcomes concretes tensile weakness allowing increased load carrying capacity over longer spans than ordinary reinforced concrete construction. The advantages and disadvantages of precast and pre-stressed concrete are discussed in Tables 3 and 4. (Anonymous, ; Graduck, 1970)

Table 4: Precast Concrete Characteristics

Precast Concrete – In General			
Advantages		Disadvantages	
Properties	*Description*	*Properties*	*Description*
Maintenance	-Doesn't require upkeep	Heavy	-Require large cranes to lift -Can be put together in smaller pieces
Fireproofing	-Has high degree of fire resistance -Non combustible	Corrosion	-Reinforcement bars susceptible to corrosion, iron must be coated
Quality Control	-Easy to produce concrete that meets requirements -High quality because of controlled conditions in factory	Complicated Design	-Difficult connections -Small Margin of error -Limited design flexibility
Durability	-Can be designed for different exposures -Designed against weathering action, chemical attack and abrasion	Elasticity	-Design assumptions are rather indefinite
Cost	-Competitive with steel in cost	Crack	-Weak crack resistance, cracks at working loads -Increases corrosion on reinforcement and concrete -Low tensile strength
Constructability	-Rapid speed of erection -Can be erected year round -Whole building can be precast		
Compression	-High compression strength		
Aesthetics	-Flexible, can be a variety of textures, colors, finishes, and insert options -Plastic, can mimic other materials		
Design	-Flexible: long-span capabilities -Open interiors		
Energy Efficient	-High thermal mass -Insulation		

2.13.3 Steel Trusses

The new Center consists of a 29,000 square foot gymnasium where the ceiling above spans more than 100 feet with no vertical support. A popular and economical structural element used to span great distances is a truss. A truss is a framework of structural members consisting of top and bottom chords and diagonal web members. (Integrated Publishing, 2010) In roof trusses, the top chord acts as a roof rafter and the bottom chord serves as a ceiling joists. (Truss-frame.com, 2003)

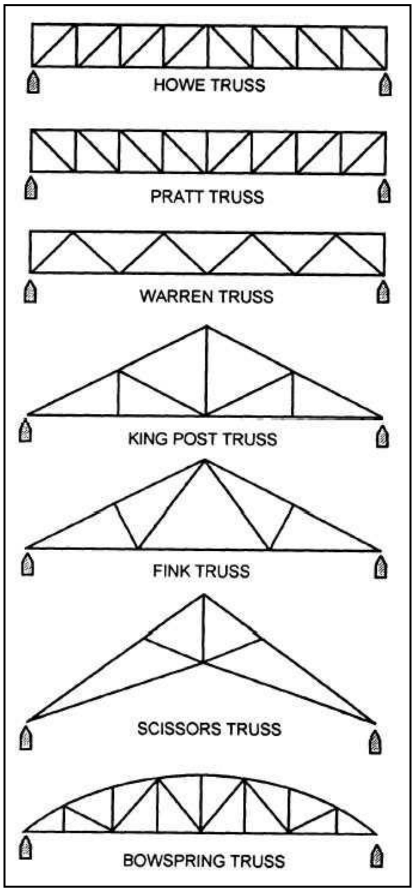

Figure 11: Common Roof Truss Systems (Integrated Publishing, 2010)

Trusses can be fabricated to conform to diverse shapes and sizes which make them a versatile construction element. Many different shaped trusses exist and are utilized depending on the application and the surrounding components. Steel trusses are used for many applications, including bridges, floor systems, and most commonly, roof systems. Figure 10 shows seven popular truss types used for roof systems.

The roof system to be implemented in one location of the new Center consists of over ten flat trusses similar to that of the Warren Truss. This truss system, shown in Figure 11, will be located above the gymnasium floor. Perpendicular to the trusses is a set of cross-bracing elements which resemble another truss. These cross-braces consist of top chords, bottom chords, and web members where necessary. Trusses can be used when MEP systems, such as ducts and pipes, are included in the roof system. There is little material used in a truss and therefore equipment can run along a ceiling, through a truss, with little or no interference. The versatility of a truss makes it an easy

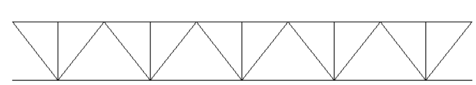

Figure 12: Truss Design Used in New Center

alternative to any roof or ceiling system, especially in the case of the new Center where steel is a main component of the buildings structure.

2.13.3.1 Alternative Design in WPI's New Recreation Center

In order to implement a truss system as an alternative design to the precast concrete arches in the natatorium of the Center, several aspects must be considered. The design criteria includes:

1. Design Loads – The first step in designing a truss is analyzing the loads acting on the truss. What is the truss supporting? Are there vertical and lateral loads? How will the loads be found or calculated? This type of information can be found in the structural drawings provided by Cannon Design, the designer of the project. The designed truss must meet all codes and requirements.
2. Building Codes – Massachusetts building codes must be adhered to determine standard load criteria which are not stated in the drawings or project specifications. The designed truss must meet all codes and requirements.
3. Constraints – There are physical limitations posed by the unique conditions of the Center that must be noted while designing the truss.
    a. Size of the truss – The truss cannot exceed a certain size, which should match the size of the concrete arches.
    b. MEP equipment and other interferences – Similar to the arches, the alternate design must accommodate the MEP equipment which runs along the ceiling.
    c. Connections – There are many different types of connections that must be considered while constructing the truss in the natatorium. How will the trusses be supported? How will the truss system interact with the existing structure opposed to the precast arches? How are the members of the truss joined?

d. Corrosion resistance – By replacing concrete with steel in the natatorium, the steel will become more susceptible to corrosion. An application which is aesthetically pleasing and leaves room for fire proofing must be considered.
e. Cost – In order to design a practical alternative the cost of the truss must be competitive with that of the precast concrete. Additional cost must be considered for fireproofing and corrosion resisting materials.

4. Safety Conditions – As mentioned above, the truss must be fireproofed for safety reasons. This may be a challenge to design since the truss will also require corrosion resistance.
5. Building Layout – The layout of the building plays a large part in determining the size of the truss and the necessary cross-bracing. How far will the truss be spanning? Is cross bracing necessary?

Once a truss is designed using the above criteria, it should be evaluated to ensure that the truss is adequate and practical in the application that it is being used. The alternative should also be compared with the original design to determine which is preferred. The following criteria should be considered to evaluate the alternative truss design.

1. Cost – Does the alternative increase/decrease the cost of the overall project? Are there long term costs associated with maintenance and insurance policies?
2. Schedule – How does the alternative affect the overall schedule of the project? Since the majority of the Center will be constructed of steel we will assume that the steel is accessible for purchase and delivery to the site. Will the trusses need pre fabrication? Will this affect lead time?
3. Maintenance – Will the alternative require more maintenance by the Owner?
4. Aesthetics – If the truss is exposed, how will it look? Will it look unpleasing or out of place? BIM technology must be used to visualize the expected appearance of the alternative.

5. Constructability – How will the erection of the truss system differ of that of the precast arches? Will additional equipment be necessary? Can the truss be easily erected? Is there storage on site large enough to accommodate prefabricated steel members?

2.13.4 Building Codes and Safety Regulations

Massachusetts State Building Code is based on the 2009 *IBC* (*International Building Code*), *IEBC* (*International Existing Building Code*), *IFC* (*International Fire Code*) and *IECC* (*International Energy Conservation Code*). (International Code Council, 2010) The building code is regulated by the Massachusetts BBRS or Board of Building Regulations and Standards. *The International Codes* are adopted from the International Code Council (ICC), a nonprofit organization that provides technical, educational, and administrative support to government departments and agencies engaged in comprehensive, coordinated building safety, fire prevention and energy efficiency codes. (International Code Council, 2010) The parties involved with the new Center are mandated to follow these codes.

On site, safety regulations have to be met. OSHA or Occupational Health and Safety Administration sets guideline regulations and enforces them to ensure safe and healthy working conditions. In OSHA's guidelines there are specific standards for the construction industry. (United States Department of Labor, 2010) Gilbane must abide by these regulations to prevent costly injuries on site. For example, workers not wearing proper safety gear such as harnesses can fall from heights causing injury or death. This would stop project work and have an emotional toll on the construction personnel while bringing the mood of the construction team down slowing work

Chapter 3 – Methodology

3.1 Project Objectives

The MQP project at hand is comprised of two parts concerning the construction and maintenance of the new Recreation Center. The first part will utilize project manager's techniques to incorporate BIM technology in addressing obstacles that facilities management currently face. In addition, Owner's meetings and MEP coordination meetings will be attended to observe the role of each party during construction. The second part will display structural aspects by proposing an alternative design in the natatorium of the new Center.

Our team has created a set of objectives relating to the above topics to complete project. These objectives are:

- Understand important criteria involved in managing a construction project
- Explore the use of BIM technology to improve facilities management by identifying an efficient approach to compile "as-built" information into an easily accessible database
- Create BIM prototype for facilities management
- Design one alternative steel structure to replace precast arches in natatorium
- Create construction schedule and cost estimate for steel design alternative
- Complete MQP final report

3.1.1 BIM and Facilities Management

BIM technology has been incorporated throughout the design and construction phases of the Center. Cannon Design has used BIM during pre-construction for the initial design, while Gilbane has used the technology for the 3D coordination of MEP, fire protection and structural disciplines. Gilbane has chosen Navisworks, a specific BIM integrating software, to detect clashes between design components and to visualize the project through its walkthrough capabilities and 4D displays. However, no intent has been expressed to incorporate the BIM model for other purposes such as the storing of up-to-date information for WPI. The BIM portion of this project refers to the investigation of the advantages of incorporating BIM technology into the construction phase of a project along with the potential for post construction applications in facilities management. Extensive consultation with field professionals combined with familiarization with the specific tools and software will be the critical pieces to the completion of this portion of the project. Initially consulting Mr. Alfredo DiMauro and other personnel from the Department of Facilities we will collect information crucial to the operation of the Department of Facilities. From this information, research will be conducted on the specific components designed into the new Center. Simultaneously the team will attend Gilbane's MEP coordination meetings and the project's Owner's meetings to investigate the advantages and limitations of utilizing BIM during the construction process. Our main focus will be to analyize how the use of Navisworks facilitates this phase of the project. We will also hold discussions with Timothy Grant and Bill Atkins to enhance our knowledge of Autodesk Revit and Navisworks.

A prototype of the new Center will be developed as a representation of the entire structure, from a design and post-construction perspective to demonstrate the benefit of incorporating BIM technologies into the construction process. A mechanical room containing pool operation and maintenance equipment will act as the focus of the prototype from a facilities management standpoint. This model will include information desired by the Department of Facilities for routine repairs and maintenance as well as specific component information such as product numbers and warrantee information. Parallel with this portion of the project the alternative structural design for the precast concrete arches will be integrated into the current BIM design model to demonstrate BIM's visualization capabilities of investigating "what-if" and alternative design questions and possibilities. BIM will also allow the team to effectively investigate cost and schedule implications associated with the alternative design.   Through these two examples and a white paper the potential of BIM technologies will be evaluated from two aspects- during the construction phase and post-construction cycles of the structure.

3.1.2 Alternative Design

In the current design of the new Center, eight precast concrete bents or arches support the ceiling above the natatorium and the floor of the gymnasium.   The arches are a structural feature which can be altered by implementing an alternative design using steel trusses in place of the precast concrete, similar to the design located at the gymnasium ceiling, supporting the roof.   There are many advantages to constructing these supporting elements from steel rather than concrete.

Currently the new Recreation Center has two contracts, one for steel and one for concrete.   If an alternative steel design was implemented for the concrete arches and double tee beams over the pool area, only one contract would be necessary.   One contract could reduce the cost of the project for several possible reasons.   Since there would be more steel involved in the construction, a bulk price may be available resulting in a less expensive unit price.   Also, one contract could simplify the coordination of the construction process and schedule.   For instance, as of now the steel is planned to arrive on October 19th and the concrete is on target to be constructed on November 1st.   With two separate contracts, there will be two groups of workers on the construction site as well as two cranes to lift the steel and concrete. This will prove to be a very complicated portion of the construction phase where much communication, coordination, and strict safety measures will be necessary.   Even though two sections of the building will be constructed simultaneously with two contracts, any clashes between the two contractor's schedules or equipment would result in delays. With one contract for steel only, this problem would be averted, potentially saving time and money.

The steel alternative will consist of multiple trusses and perpendicular bracing components if necessary. The truss design can be compared to the system above the basketball courts on the 5th floor. We will take into account the current organization of the MEP equipment in the natatorium and Gilbane's prior experiences with long-span trusses in order to determine the most practical truss type. A structural analysis will be performed in order to determine the sizes of the truss elements necessary to support the building loads. The design loads will be obtained from the current construction documents and verified using Massachusetts Building Codes and the 2005 American Institute of Steel Construction (AISC) Manual of Steel Construction (13th Edition). According to the Cannon structural drawings, the trusses in the gymnasium were designed using AISC LRFD procedures (Cannon Design, 2010). In order to be consistent, we plan to also use LRFD procedures when designing the alternative in the natatorium.

In addition to the design alternative, a schedule demonstrating the construction process will be created along with a cost estimate of the material, equipment, and labor. This schedule and cost estimate will be compared to the current project schedule and cost estimate of the concrete arches. Differences in these aspects will be analyzed to determine the preferred solution. In order to give a visual representation of the design alternative and its effect on the project schedule and cost a 5-dimensional (5D) model will be created using Revit, showing the duration of each phase of construction along with its cumulative cost to date.

3.1.3 Project Meetings

The new Center's Owners meetings and Mechanical, Electrical, and Plumbing (MEP) meetings will be attended throughout the duration of our MQP. Attending these meetings will allow our project team to gain a real world look into the construction process from two different angles: the angle of WPI (the Owner) and as a member of the design team. These meetings will also give our project team insight into the social relations, interactions, and organizational issues between the companies involved with the project. Additionally the meetings and resulting meeting minutes will act as resources to document the latest activities and decisions with the new Center. All companies involved in the construction of the new Center are required to understand how to use BIM, as well as be able to make the necessary adjustments to their plans via BIM. Attending these meetings will illustrate to our project team how BIM can be used to facilitate the design and construction processes, as well as to assess qualitatively whether BIM's three-dimensional capabilities actually increase the attendees' understanding and efficiency of these meetings. These observations will be compared to our notes from the interviews to look for correlating data to strengthen our arguments.

3.2 Organizational Resources

Organizing documents, resources, and writing compilations has become a crucial step in our methodology. To better organize the work over the life of our MQP, the collaboration with our advisors and our team members have invested time in the creation of organized structured file exchange portal and reference organizer. By using myWPI file exchange and Refworks, our project team plans to make the communication process more efficient.

To create efficient teamwork and integration though the use of myWPI, each team member will post major portions of the project for which the individual is responsible and from this will create folders to hold all of the material related to that particular aspect of the project. Initial experience suggests that this is an excellent and convenient method as editing changes are tracked and critiqued throughout all of the report process.

The 'Proposal' folder serves as an on-going working compilation of all materials that will be included in our final proposal, which gives our team a sense of "project tracking." MyWPI serves its purpose as a collaborative device with the advisors as well. Following the completion of our proposal, our document will be posted in the 'To Advisors" folder which informs our advisors that the proposal is ready for approval and critiquing. After direct communication meetings with advisors, minutes will be posted to show our advisors the information, which was taken from meeting as well as our understanding. Prior to meetings, agendas will be posted in order to allow our advisors time to focus on the information that we plan to discuss in the next meeting. to the intent is to conduct very efficient and orderly meetings as our team and advisors can come to meetings well prepared and focused on the issues at hand.

Refworks is an online research management collaboration tool that is designed to organize bibliographical information on a web server. This software makes it easy for all team members to log their references online and easily cite them in the project proposal and report. Refworks prevents the loss of information as to where we received help on our project and also ensures the convenience of avoiding plagiarism and last minute searching through the library to obtain and properly credit information on authors, titles, etc.

3.3 Schedule

Table 5 shows a list of the tasks that we plan to perform in order to complete our set objectives. The table also shows how we will execute all of the tasks and what resources we will use throughout the project. Figure 12 is the project schedule which includes durations and dates for all objectives and tasks to be completed during B-term. Figure 13 is a similar schedule which includes objectives to be completed during C-term. We will also create 2 Week Look Ahead schedules every week based on these schedules.

3.4 Conclusion and Deliverables

Once all of our methods are complete, we will have determined the potential of using Building Information Modeling in WPI's Department of Facilities. Using the collected information, we will compile a white paper discussing how BIM can help the Facilities Department along with a prototype of a mechanical room in the new Center for visual aid. Interviews will give our team professional insight into BIM and how it is affecting the facilities management industry. Our proposed alternative design presented in a final report will provide our team with insight into the design process and how designs can be represented in BIM as well as allow the team to determine schedule and cost implications due to this alternative. Keeping organized will be key to staying on track and completing our project successfully. Overall, these methods will allow us to determine the prospective uses of BIM for WPI's Department of Facilities and to investigate an alternative steel design and its impact on the new Center's construction schedule and cost.

Methodology		
Task	**Plan of Action**	**Resources**
Understand important criteria involved in managing a construction project		
Observe relationships between parties, safety issues in construction, and obstacles pertaining to politics, scheduling, etc.	Attend project meetings	Project teams
Project Proposal		
Edit and revise as necessary	Group meetings, edits, and writing	Group members
Incorporate BIM technology to improve facilities management		
Investigate FM current software and practices	Interview WPI facilities management staff	Fred DiMauro, Elizabeth Tomaszewski, Brian D. Wilson, Mike Lane, etc.
Determine current close-out procedures and documents given to owner	Interview Gilbane team	Neil Benner, Justin Gonsalves, Melissa Hinton
Determine uses of Navisworks and Revit relating to the Center	Interview with Gilbane BIM specialist, research	Bill Atkins, Revit, Navisworks
Determine uses of BIM software in post-construction stages	Research case studies, analyze past reports	Internet/Library, Case Studies, Mendez Thesis
Become familiar with Revit/BIM	Work with Tim Grant and Bill Atkins, Review tutorials, practice using software	Revit, Tim Grant, Bill Atkins, Autodesk website
Write framework/manual to help FM use BIM in future	Combine research, interview information, and knowledge of Revit to write framework	Past research, Revit
Create BIM facilities management microcosm		
Determine equipment or mechanical room approved or installed early in construction	Consult Gilbane team, review schedule and submittals	Gilbane
Acquire equipment specific information included in close-out documentation	Contact eqiupment manufacturer, review submittals	Equipment Manufacturer, Gilbane
Create BIM model with operation, maintenance, and warrantee information for facilities management use	Add all collected information to current Revit file from Cannon, transfer Revit file to viewable, user-friendly software for FM usage	Revit, User-friendly software (Autodesk Design Review)
Design alternative steel structure to replace precast arches in natatorium		
Determine and verify loads/constraints on current design	Analyze plans and acceptable design loads	REVIT, Cannon 2D Plans
Determine steel constraints and solutions in natatorium	Research case studies and similar structures. Research fire proofing and corrosion applications with steel	Internet/Library, FPE department, MA Building Codes
Design practical solution, including type (beams, truss, etc) and sizes	Use knowledge of steel design combined with design loads and structural constraints	CE 3006 Text, AISC Steel Construction Manual (LRFD Procedures), Cannon Structural Drawings, MA Building Codes
Determine feasibility and constructability of proposed design	Consult Gilbane team	Gilbane
Create construction schedule and cost estimate for design alternative		
Determine schedule components for alternative	Obtain and analyze current schedule (Gantt chart), research steel fabrication and installation criteria, research steel lead times/erection durations	Neil Benner, Gilbane's current schedule, Steel fabrication company, Steel subcontractor
Create construction schedule for alternative	Organize scheduling components and assign each component a duration	Primavera Software
Determine cost for alternative	Speak with Cannon estimators or subcontractor, research unit prices, direct, and indirect costs	Estimators, RS Means books or online cost data
Determine differences between alternative and actual structure in respect to cost and schedule	Compare Gilbane estimated cost and schedule with the estimated cost and schedule determined for the alternative	Gilbane
Complete MQP final report		
Ensure all project scope components have been completed	Review project objectives, analyze objectives and capstone criteria, make sure all criteria and objectives have been met	Group members, MQP Capstone Requirements
Develop outline for final report	Review organization of past MQPs and compare with the project scope	Past MQP reports
Write final report	Assign sections of report to group members, incorporate sections of proposal to final report where applicable, document all results	Microsoft Office, MQP Proposal, Group members
Edit and revise as necessary	Group meetings, edits, and writing	Group members

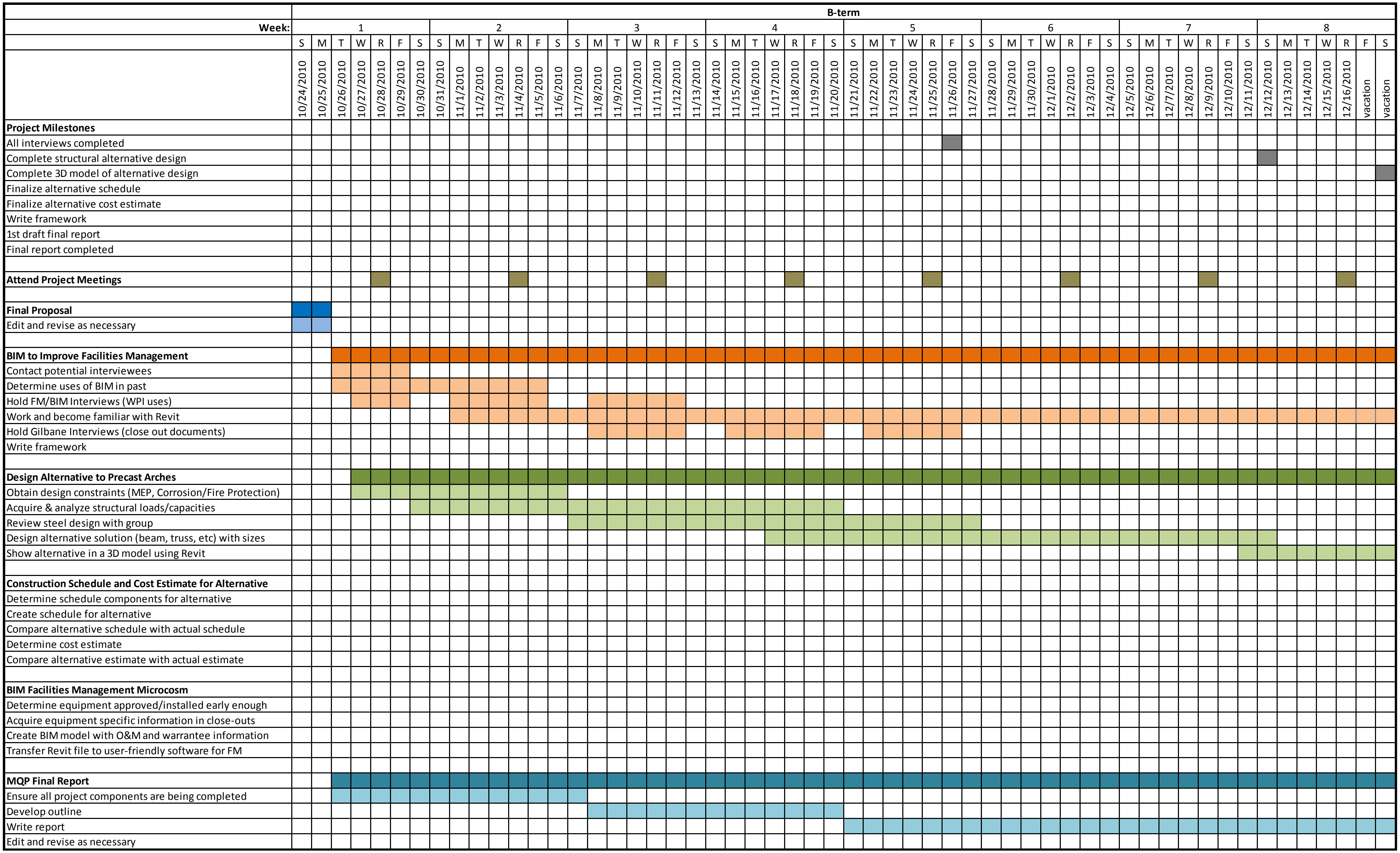

Figure 13: Project Schedule for B-Term

	C-term																																																						
Week:	1							2							3							4							5							6							7							8						
	S	M	T	W	R	F	S	S	M	T	W	R	F	S	S	M	T	W	R	F	S	S	M	T	W	R	F	S	S	M	T	W	R	F	S	S	M	T	W	R	F	S	S	M	T	W	R	F	S	S	M	T	W	R	F	S
	vacation	vacation	vacation	vacation	1/13/2011	1/14/2011	1/15/2011	1/16/2011	1/17/2011	1/18/2011	1/19/2011	1/20/2011	1/21/2011	1/22/2011	1/23/2011	1/24/2011	1/25/2011	1/26/2011	1/27/2011	1/28/2011	1/29/2011	1/30/2011	1/31/2011	2/1/2011	2/2/2011	2/3/2011	2/4/2011	2/5/2011	2/6/2011	2/7/2011	2/8/2011	2/9/2011	2/10/2011	2/11/2011	2/12/2011	2/13/2011	2/14/2011	2/15/2011	2/16/2011	2/17/2011	2/18/2011	2/19/2011	2/20/2011	2/21/2011	2/22/2011	2/23/2011	2/24/2011	2/25/2011	2/26/2011	2/27/2011	2/28/2011	3/1/2011	3/2/2011	3/3/2011	3/4/2011	vacation
Project Milestones																																																								
All interviews completed																																																								
Complete structural alternative design																																																								
Complete 3D model of alternative design																																																								
Finalize alternative schedule																																																								
Finalize alternative cost estimate																																																								
Write framework																																																								
1st draft final report																																																								
Final report completed																																																								
Attend Project Meetings																																																								
Final Proposal																																																								
Edit and revise as necessary																																																								
BIM to Improve Facilities Management																																																								
Contact potential interviewees																																																								
Determine uses of BIM in past																																																								
Hold FM/BIM Interviews (WPI uses)																																																								
Work and become familiar with Revit																																																								
Hold Gilbane Interviews (close out documents)																																																								
Write framework																																																								
Design Alternative to Precast Arches																																																								
Obtain design constraints (MEP, Corrosion/Fire Protection)																																																								
Acquire & analyze structural loads/capacities																																																								
Review steel design with group																																																								
Design alternative solution (beam, truss, etc) with sizes																																																								
Show alternative in a 3D model using Revit																																																								
Construction Schedule and Cost Estimate for Alternative																																																								
Determine schedule components for alternative																																																								
Create schedule for alternative																																																								
Compare alternative schedule with actual schedule																																																								
Determine cost estimate																																																								
Compare alternative estimate with actual estimate																																																								
BIM Facilities Management Microcosm																																																								
Determine equipment approved/installed early enough																																																								
Acquire equipment specific information in close-outs																																																								
Create BIM model with O&M and warrantee information																																																								
Transfer Revit file to user-friendly software for FM																																																								
MQP Final Report																																																								
Ensure all project components are being completed																																																								
Develop outline																																																								
Write report																																																								
Edit and revise as necessary																																																								

Figure 14: Project Schedule for C-Term

Appendix

Facilities Management Interview (Mendez, 2006)

<u>Interviewees</u>: Elizabeth Tomaszewski, Brian D. Wilson, Christopher L. Salter, David H. Messier, and Mike Lane

<u>Interview Questions:</u>

What is the current method of operations and maintenance?

What information about components of a building is provided from the designer or constructor?

What do you think of the information that is provided?

How is the information provided?

How do you use it?

What are the areas of a building that are most commonly addressed?

What are the current practices for addressing these areas?

What are the issues with the current system?

What impact would building information modeling have on the current management style?

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Gilbane Interview (Mendez, 2006)

Interviewee: Neil Benner (Project Manager)

Interview Questions:

What will Gilbane give to WPI according to the contractual requirements?

Is this standard for the industry or just for WPI?

What additional item do you think should be given to the owner?

What kind of requirements are inconvenient to produce?

How involved is the documentation process?

What information could you give that you could have given the owner/client at the beginning of project, design and/or construction?

If something goes wrong after building construction is complete, what does Gilbane do?

What do you think of the BIM?

Are there any pieces of equipment (pump room equipment) which have been submitted and approved or that will be getting installed soon?

Gilbane Interview

<u>Interviewee</u>: Bill Atkins

<u>Interview Questions:</u>

How long have you been working with Navisworks and BIM?

How comfortable are you with them?

How does the 3D models compare to 2D plans?

What issues has BIM smoothed out in the design process?

Has BIM made a major impact of efficiency on Gilbane?

Are tasks or issues resolved faster with BIM?

How is Navisworks being used in the new Center project?

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Appendix B – Interview Questions and Responses

Interview #1 – November 9, 2010
Elizabeth Tomaszewski

As Facilities Systems Manager, what are your responsibilities?

1. Sustainability Coordinator
2. Facilities Systems Manager
    a. Operating Maximo work order system
    b. Customer service for maintenance of campus
    c. Generates statistics for work orders to improve the performance process
3. Building library for drawings and building plans
4. Warehousing deployment of furniture on campus

- **What decisions do you make?**

Work orders – how to operate customer service system in an optimal fashion. Make sure that Maximo is running optimally. Currently staff is being trained in Maximo to learn the basic functions – really hitting the ground running. The priority for managers is preventive maintenance and currently at WPI a scheduled maintenance program has yet to be established**.** The theory is, and I believe it is true, that if you schedule your maintenance you avoid costly downtime and repairs later on. Looking to implement preventative maintenance for all the chillers across campus, which would help schedule maintenance for about 20 locations and their associated components that would comprise costly repairs.

Property management system, called *Macems,* which keeps track of all government-funded assets. Macems is not currently running optimally and the Department is looking to use Maximo instead.

Building library for drawings – need student resources to build library. Everything the Department has now is paper; huge volume of drawings that is uncategorized. We're beginning to develop library and categorizing system, which will be helpful for the Department, students, and contractors. WPI feels that they are behind in the industry, but after talking to other universities they've realized that they are really not that far behind.

Let me tie the work order system in with the library of drawings; when we generate a work order it is useful to attach drawings, specifications, warrantee information, or the contract to the work order. Strong hope for future that the Department will learn how to connect drawings, warrantees, SLA's, etc to work orders. This is getting to be pretty cutting edge for Facilities Service Providers.

Furniture – recent to facilities management. When department gets renovated, Facilities determines new furniture and assigns old furniture to be placed elsewhere. Want to have standard, coordinated furniture on campus.

- **What type of information do you handle?**

Work orders – daily time sheets (reports from tradesmen and they tell what tradesmen work on). Important information is the work order information (work order #, status, hours worked, materials used, tools used, cost of materials, etc.) All this information must go into Maximo. This information is looked at by the Department in a number of ways - looks at work orders as a "deficiency log" which measures performance of tradesmen and facilities progress. Also evaluates the flow of paperwork/performance of staff associated with the Department.

I also handle customer complaints – quality of work or not doing work. Currently implementing program to notify customer when a problem will be addressed.

Drawings from projects that will be added to the library.

What is your relationship with the other members of the Department of Facilities?

MEP supervisor (Brian), Manager of Grounds, Director of Custodial Services, and tradesmen report to Mike Lane

Mike, Project Manager (Chris Alter), myself, Dave Messier, Manager of Laboratory Safety report to Fred DiMauro

Meet regularly – PMs meet every other week. Group meets regularly to discuss Maximo.

Mike, Brian, and Liz talk most regularly about Maximo and tradesmen procedures. I am also in regular contact with the Project Manager does a lot of stuff which results in drawings and building plans.

Explain our project:

As you may already know, our team is experimenting with Building Information Modeling to research how WPI, as an Owner, could benefit from it. The first part of our MQP will exemplify the benefits of using BIM in pre-construction phases of all future construction projects by showing how the product facilitates with analyzing alternative designs.

The second part of our project will focus on the closeout phase and investigate how this new technology can improve WPI's Department of Facilities information database, by experimenting with BIM's information storage feature.

(Present list of contract documents)

How do you store the information given to you after a building is completed?

Two types of libraries: Paper Library and Digital Library. If something is digital, our Department requires a paper copy as well.

"Book plans" - PDF drawings of the buildings, floor plans on campus. This book is referenced CONSTANTLY during the day for locations and measurements. Not only for inventory, but for resources like Facilities Service Vans.

- **How is information provided?**

According to specs, the Owner receives this information from the Contractor.

- **Are there additional items you feel could be included?**

Most important thing for FM is the floor plans with windows, doors, etc. Operating procedures and warrantees are definitely needed. If our project team would like to get high end, I'd like to see this information tied with work orders (allocate inventory and parts) in order to allocate inventory to a specific job or work order or see how much inventory exists on campus in order to use in future.

- **How is this information used after the building is occupied by WPI?**

This question was previously answered.

What elements of a building are most commonly addressed for preventive maintenance/call-in work orders?

Currently our Department doesnt do much preventive maintenance application. HVAC is only preventive, but extremely limited. We would like to have a plan in place to address PMs by June 2011. Start with chillers as a prototype. There are problems with Maximo; it takes resources to load and manage data in Maximo. Something we must do is learn the software before we can use it correctly.

- **What information is usually referenced concerning these areas?**

What are the current practices for addressing these areas?

Very basic: get a schedule of work that needs to be done by tradesmen, put schedule into Maximo, some assets are identified, run those through Maximo to create work orders as needed. This is extremely fundamental. Want a PM in system for the 40 to 50 WPI vehicles on campus for oil change, etc.

- **Do you feel that this is time efficient?**

Not really.

- **Do you think there's a better way?**

What impact would building information modeling (BIM) technology have on the current management style?

I seriously wish that I had more time to learn the software. Based on the limited amount of time that I've spent with the software and read in articles I've learned how helpful and powerful the software is. I think that BIM is absolutely the way to go. It can provide answers and much more transparency than current systems in use. There's not a lot of room for questions because everyone is talking together and

I think that's really where we want to be. With the current system there are too many disconnects that can occur when not talking together.

- **Does BIM make this process more or less efficient?**

From what I've learned BIM makes this process more efficient.

Since you have been learning to use the viewer software (Design Review), do you feel it would be feasible for the majority of the Department of Facilities to learn this software?
Aboslutely.

- **What are your impressions of the software as a means to view and have access to model information?**

Need a lot of time to learn BIM. I wish had more time and information. I do not have a very accurate idea of the scope of BIM's power. Collaborates owner, architect, contractor, etc. Everything is tied together and laid out, not much room for questions. Less disconnects with BIM. Forces everyone to work together to better the building. Excited to learn more.

Leaking Pipe Example: Often times we don't know if it's a HVAC issue, plumbing issue, or roof leak. Evaluation process takes a lot of experience. Initially HVAC guys are sent to evaluate a leaky pipe (for example) and say whether or not its HVAC or plumbing.

I was very impressed with the software. It was fun. I enjoyed walking through the building. What I am particularly interested in is if there were changes to something, have ability to document changes. I think that would be very beneficial to the Department.

- **Did you initially find it hard "walking" around the building?**

Yes, that's not my first nature being mechanical. It was initially awkward but once you can walk, you can drive. It is pretty intuitive. I think that one downside to the software is it may be too much fun and staff may play with it, once they get comfortable.

I'd like to put some emphasis on the fact that if were looking to implement a new system we must have the resources to enter the data and manage the data when its in.

Interview #2 – November 10, 2010
Justin Gonsalves

What information does Gilbane receive that could be beneficial for the Owner to receive prior to construction or installation of equipment.
Before installation I think it would be O&M Manuals for all of the equipment would be huge. The big that we do with Gilbane is starting close-out at the beginning of project; we try to get subcontractors to submit all information to Gilbane as soon as possible so can be done that project will be done at end of construction. It is hard to motivate construction team at the final stages of the project in order to receive all of this information.

How involved is the close out documentation process?
It is pretty involved. Specifications list everything. Different owners want different things. For the Recreation Center this process wont be through the roof ridiculous – this is pretty standard for the Center, but it is dependent on the client.

- **How much time/effort is spent gathering information on equipment to organize for the Owner?**

As stated before, Gilbane strives to begin this at the start of the project. Overall, gathering the information is very tedious. Ideally, we should start close out or optimize close out when the project has the most staff on the project, which is typically in the middle of the duration of the project.

Are the contents of the contractual agreements standard for the industry or just for WPI?
Standard.

- **What kinds of requirements are inconvenient to produce?**

O&Ms are always a pain because the subcontractors are middleman between the fabricator or manufacturer and the Owner. Currently, we are trying to require the O&M information upon delivery of equipment or material. On top of retainage (for leverage) Gilbane assigns a cost to the O&M therefore if they are not received, subcontractors will not be fully paid.

What additional items do you think could be provided to the Owner for their benefit at close out?
At Gilbane, we are always trying to improve providing more information for the Owner's benefit. Some owners get overwhelmed with the amount of close out information. Warrantees and how to maintain warrantees – we like to simplify it for the Owner so that they know exactly when their warrantee is up, when maintenance is required, etc. One big thing that Gilbane does is turning over all information digitally in PDF.

If something goes wrong after construction is complete, what are Gilbane's responsibilities?

WPI will contact Gilbane and then Gilbane will contact the manufacturer. Typically, WPI will contact the manufacturer directly.

- **How is the warrantee process carried out?**

N/A

What is your opinion of BIM?
The biggest benefit is BIM's ability to give someone the ability (who doesn't understand building plans) to visualize the future layout of the building. Specifically for WPI, BIM has facilitated the robot pit issue which would have delayed the project approximately 6 months and caused more headaches.

- **How do you feel about having all of the information in a large software database?**

I think that it is pretty neat. This is the first job that I have used BIM.

- **Has BIM had a noticeable impact on Gilbane's production?**

I believe that the time we (Gilbane's Project Team) spend now working out kinks through BIM's clash detection takes longer than 2D plans. However we will most likely save time further down in the project since we will be more knowledgeable before physical issues occur.

On-site I haven't seen field production being increased, because it is too early to tell, but I feel production is going to drastically increase. Currently it is just a hope at this point. Most of the subcontractors onsite haven't used prior to this project. It's a learning process with a long learning curve. Next job will be that much faster.

We are constructing a BIM prototype of a mechanical room for facilities management at WPI.

- **Are there any specific rooms that have component information established and accessible?**
  - Room with chillers and boilers: A103, Fire/$H_2$0 room – pumps and boilers. Room 355
  - AHU 5 (air handling unit), ERU 3 (energy recovery unit), Room 359. ERU unit is custom unit for the entire pool has its own Division 23 anything with pools.
  - Pump rooms could cause problems for modeling because they are very congested.

When was BIM first utilized for the MEP coordination process by Gilbane?

- **Do you feel this is an effective approach for clash detection?**

Yes, it's pretty awesome. Hard to keep focus in meetings but its definitely worth while. You can decipher what an actual conflict is and what's just a little issue with the program. One problem that we've seen is that if all the models are not definitely up to date with the subcontractors, conflicts will arise that may have already been addressed in past meetings.

- **How could it be improved?**

On this job, coordinating the schedule with the model. CM and Subcontractors are old school so there isn't enough time to learn programs completely.

- **What are the advantages/disadvantages of using BIM? (For example, long learning curve, limited subs can use BIM, simplifies coordination in the field, etc.)**

Nothing specific stands out. Learning curve is the worst, which causes miscommunication between the team. This is Bill Atkins first job using BIM.

- **Was knowledge of BIM required by Gilbane for all design trades?**

At beginning of job, wasn't going to do BIM. Asked subcontractors during the interview process. Most said yes but they would have to learn it. Nowadays you almost have to have BIM knowledge because most jobs use it. It was not required on this project by WPI.

- **Does this affect cost?**

Subcontractors are benefitting from learning, but it takes more time. Cost is really high for the huge computer and the large TV. If Gilbane buys BIM modeling from subcontractors, they will estimate the time/cost implications due to BIM. I feel that it is worth spending the extra money at the beginning in order to save headaches and cost at the end or through construction.

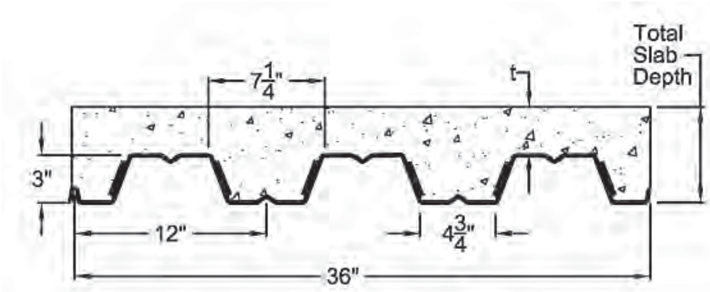
I-build program – electronic punch list – Gilbane is trying to implement now for this job for punch list. Want to use BIM for punch list. Get everyone on the same page (designer and contractor).

Biggest benefit is for people who don't have thorough understanding of 2D plans.

Appendix C – Structural Calculations and Product Data

3 VLI

Maximum Sheet Length 42'-0
Extra Charge for Lengths Under 6'-0
ICBO Approved (No. 3415)



Interlocking side lap is not drawn to show actual detail.

STEEL SECTION PROPERTIES

Deck Type	Design Thickness in	Deck Weight psf	Section Properties I_p in^4/ft	S_p in^3/ft	I_n in^4/ft	S_n in^3/ft	V_a lbs/ft	F_y ksi
3VLI22	0.0295	1.77	0.730	0.414	0.729	0.426	1528	50
3VLI20	0.0358	2.14	0.920	0.534	0.919	0.551	2698	50
3VLI19	0.0418	2.50	1.104	0.654	1.102	0.676	3678	50
3VLI18	0.0474	2.84	1.254	0.770	1.252	0.797	4729	50
3VLI16	0.0598	3.58	1.580	1.013	1.580	1.013	5309	40

(N=9.35) NORMAL WEIGHT CONCRETE (145 PCF)

TOTAL SLAB DEPTH	DECK TYPE	SDI Max. Unshored Clear Span 1 SPAN	2 SPAN	3 SPAN	Superimposed Live Load, PSF Clear Span (ft.-in.) 7'-0	7'-6	8'-0	8'-6	9'-0	9'-6	10'-0	10'-6	11'-0	11'-6	12'-0	12'-6	13'-0	13'-6	14'-0
	3VLI22	9'-2	10'-7	11'-8	216	195	176	161	148	109	99	90	83	76	70	64	59	54	50
5.00	3VLI20	10'-8	12'-11	13'-4	241	216	196	178	163	150	139	129	93	85	78	72	66	61	57
(t=2.00)	3VLI19	12'-0	14'-4	14'-7	265	237	214	194	178	163	151	140	131	122	115	79	73	67	62
45 PSF	3VLI18	12'-10	15'-1	15'-1	289	261	238	218	201	186	173	161	151	142	134	127	92	86	80
	3VLI16	13'-5	15'-7	15'-11	327	294	267	243	223	206	191	178	167	156	147	139	132	96	89
	3VLI22	8'-9	9'-8	10'-11	247	222	201	184	137	124	113	103	94	87	80	73	67	62	57
5.50	3VLI20	10'-1	12'-4	12'-9	275	247	223	203	186	171	159	116	106	97	89	82	76	70	65
(t=2.50)	3VLI19	11'-4	13'-8	14'-2	302	270	244	222	203	186	172	160	149	107	98	90	83	77	71
51 PSF	3VLI18	12'-5	14'-7	14'-7	330	298	271	248	229	212	197	184	173	162	153	112	105	98	92
	3VLI16	12'-9	14'-11	15'-5	373	335	304	277	255	235	218	203	190	178	168	159	117	109	102
	3VLI22	8'-4	8'-10	10'-1	277	249	226	171	154	140	127	116	106	97	89	82	76	70	65
6.00	3VLI20	9'-8	11'-10	12'-3	309	277	250	228	209	193	143	130	119	109	100	92	85	79	73
(t=3.00)	3VLI19	10'-10	13'-2	13'-7	339	304	274	249	227	209	193	179	131	120	110	102	94	87	80
57 PSF	3VLI18	11'-10	14'-2	14'-2	370	334	304	279	257	238	221	207	194	182	136	126	118	110	103
	3VLI16	12'-2	14'-4	14'-10	400	376	341	311	286	264	245	228	213	200	189	141	132	123	115
	3VLI22	8'-0	8'-3	9'-4	307	277	251	190	171	155	141	129	118	108	99	91	84	78	72
6.50	3VLI20	9'-3	11'-5	11'-9	343	307	278	253	232	174	158	144	132	121	111	103	95	87	81
(t=3.50)	3VLI19	10'-4	12'-8	13'-1	377	337	304	276	252	232	214	159	146	134	123	113	104	96	89
63 PSF	3VLI18	11'-4	13'-9	13'-10	400	371	338	309	285	264	246	229	215	162	151	140	131	122	115
	3VLI16	11'-7	13'-10	14'-3	400	400	378	345	317	293	272	253	237	222	169	157	146	136	128
	3VLI22	7'-9	7'-8	8'-8	338	304	233	209	188	171	155	142	130	119	109	101	93	86	79
7.00	3VLI20	9'-0	10'-11	11'-4	377	338	305	278	255	192	174	159	145	133	122	113	104	96	89
(t=4.00)	3VLI19	10'-1	12'-3	12'-7	400	370	334	303	277	255	236	175	160	147	135	124	115	106	98
69 PSF	3VLI18	11'-0	13'-3	13'-6	400	400	371	340	313	290	270	252	236	178	166	154	144	135	126
	3VLI16	11'-4	13'-4	13'-9	400	400	400	379	348	322	298	278	260	200	185	172	161	150	140
	3VLI22	7'-7	7'-2	8'-2	368	331	254	228	205	186	169	154	141	130	119	110	101	93	86
7.50	3VLI20	8'-9	10'-2	11'-0	400	368	333	303	231	209	190	173	158	145	134	123	113	105	97
(t=4.50)	3VLI19	9'-10	11'-10	12'-2	400	400	364	331	302	278	209	191	175	160	147	136	125	116	107
75 PSF	3VLI18	10'-9	12'-10	13'-3	400	400	400	370	341	316	294	275	210	195	181	168	157	147	138
	3VLI16	11'-0	12'-11	13'-4	400	400	400	400	380	351	325	303	283	218	202	188	175	164	153

Notes:
1. Minimum exterior bearing length required is 2.50 inches. Minimum interior bearing length required is 5.00 inches. If these minimum lengths are not provided, web crippling must be checked.
2. Always contact Vulcraft when using loads in excess of 200 psf. Such loads often result from concentrated, dynamic, or long term load cases for which reductions due to bond breakage, concrete creep, etc. should be evaluated.
3. All fire rated assemblies are subject to an upper live load limit of 250 psf.

GYMNASIUM FLOORING

COMPOSITE SYSTEM

CONCRETE DECKING → 6" SLAB THICKNESS (TO MATCH EXISTING CONCRETE SLAB ABOVE POOL)

STEEL DECKING → VULCRAFT (p.54)

6" DEEP SLAB → 3VLI18 (3" TO MATCH EXISTING) 18 GAUGE

SPAN = 10' (SUPPORTS 1 or 2 SPAN)

FLOOR LENGTH = 107.3' → 12 GIRDERS SPACED 10' max O.C.

GIRDER DESIGN - PARTIAL COMPOSITE

LOADS:

LL → GYMNASIUM = 100 PSF × 10' = 1000 PLF

DL:

CONC = [(145 PCF × 6"/12") − 2.84 PSF] × 1.1 (ponding) × 10' = 766.3 PLF

DECKING = 2.84 PSF × 10' = 28.5 PLF (obtained from Vulcraft catalog)

MEP + CEILING = 15 PSF × 10' = 150 PLF (obtained from CANNON structural notes)

TOTAL DL = 944.8 PLF

LOAD COMBINATION: $w_u = 1.2D + 1.6L$

$$w_u = 1.2(944.8) + 1.6(1000) = 2733.8\text{ PLF} = 2.73\text{ k/ft}$$

CRITICAL MOMENT

$$M_u = \frac{w_u L^2}{8} = \frac{2.73(24')^2}{8} = 196.56\text{ k}\cdot\text{ft}$$

unbraced length = 24' (MOST TRUSSES SPACED 19'-4" O.C.)

* This is a conservative approach. If matching existing locations, the last truss is spaced 24' from existing wall, so a larger beam may be required at end section, or to be uniform, a larger beam may be required for entire length. We want to be uniform, so use 24' in calculations

ASSUME $a = 2$

$Y_{con} = 6''$

$Y_2 = Y_{con} - a/2 = 6'' - 2/2 = 5''$

TRY W14 × 34 → Y_1 @ PNA = 7 (PARTIAL COMPOSITE) = 2.6''

↳ [$\phi_b M_n = 297\ k{\cdot}ft$, $A = 10.0\ in^2$, $d = 14.0''$, $t_w = 0.285''$] → AISC manual

@ Y2=5 & PNA=7 (Table 3-19) (Table 1-1)

CHECK CRITICAL MOMENT

BEAM WEIGHT

LL = 1000 PLF   DL = 944.8 + 34 = 978.8 PLF

$w_u = 1.2D + 1.6L \rightarrow 1.2(978.8) + 1.6(1000) = 2774.6\ plf$

$M_u = \frac{w_u L^2}{8} = \frac{2.77(24.0')^2}{8} = 199.8\ k{\cdot}ft < 297\ k{\cdot}ft$ OK

COMPOSITE CAPACITY

$\Sigma Q_n = 125^k$ (AISC Table 3-19) $f'_c = 4000\ psi = 4\ ksi$

EFFECTIVE WIDTH

$b_E < 1/4 L = 1/4(24') = 72''$

$b_E < S = 72''$

$a = \frac{\Sigma Q_n}{.85 f'_c b_E} = \frac{125}{.85(4)(72)} = 0.511$ $Y2 = 6 - 0.511/2 = 5.74''$

$Y2 = 5.5''$ $\phi_b M_n = 301\ k{\cdot}ft$

$Y2 = 5.74''$ $\phi_b M_n = 303.4\ k{\cdot}ft$ $\frac{5.74 - 5.5}{6.0 - 5.5} = \frac{x}{306 - 301} = 2.4 + 301 = 303.4$

$Y2 = 6.0''$ $\phi_b M_n = 306\ k{\cdot}ft$

$\phi_b M_n = 303.4\ k{\cdot}ft > 199.8\ k{\cdot}ft$ OK

reinforcement weight?

STUDS → 3/4" Φ STUDS, DECK IS PERPENDICULAR TO BEAM

NOTES (obtained from CANNON drawings (S503):
- stud spacing cannot exceed 24" or less than 5½"
- center studs on beam web unless >1 stud is required
- 5/8" puddle weld where no stud is indicated

Assume weak studs (more conservative)
- $R_p = 0.60$, $R_g = 1.0$
- 1 stud per rib (noted above)
- 3/4" Φ studs (S503)
- $f'_c = 4$ ksi, $F_u = 65$ ksi

AISC Table 3-21 ⟶ $Q_n = 17.2^K$

CHECK: $R_g R_p A_{sc} F_u = (1.0)(0.6)\left(\frac{\pi}{4}(3/4)^2\right)(65) = 17.23^K$ → USE $\underline{\underline{17.2^K}}$

studs, $n = \frac{\Sigma Q_n}{Q_n} = \frac{125}{17.2} = 7.3 \approx 8$ studs

FOR BEAMS SPANNING 19'-4" or 24'-0":

* SPACING IS DEPENDENT ON DECK GEOMETRY, HOWEVER SHOULD BE SPACED AT MAX SPACING OF 24" TO REDUCE # STUDS REQUIRED.
* SPACED 24" O.C., <u>10</u> STUDS ARE REQUIRED FOR 19-4" SPAN.
<u>12</u> STUDS ARE REQUIRED FOR 24" SPAN.

DEFLECTION - DURING SERVICE

LL = 100 PSF → $W_L = 100 \times 10' = 1000$ PLF $= 1.0$ K/FT → unfactored

$$M_L = \frac{(1.0\ ^K/_{ft})(24')^2}{8} = 72\ k\cdot ft$$

AISC Table 3-20 (W14×34 - PNA = 7)

$Y2 = 5.5"$ $\quad I_{LB} = 652\ in^4$

$Y2 = 5.74"$ $\quad I_{LB} = 664\ in^4$ $\quad \frac{5.74-5.5}{6-5.5} = \frac{x}{677-652} = 12 + 652 = 664\ in^4$

$Y2 = 6"$ $\quad I_{LB} = 677\ in^4$ $\quad C = C_1 = 161$ (AISC p. 3-8, Figure 3-2)

$$\Delta L = \frac{M_L L^2}{C\, I_{LB}} = \frac{(72)(24)^2}{161(664)} = 0.39" < \left(\frac{L=24}{360} = 0.8"\right) \quad \underline{\underline{OK}}$$

$$\frac{(72)(19.33)^2}{161(664)} = 0.25" < \left(\frac{L=19.33}{360} = 0.64"\right) \quad \underline{\underline{OK}}$$

DEFLECTION DURING CONSTRUCTION

DL = weight of beam = 34 PLF

LL = 766.3 PLF + (20 PSF × 10') = 966.3 PLF

↳wet concrete ↳workers + equipment

$W = DL + LL = 34 + 966.3 = 1000.3$ PLF

$$M_u = \frac{WL^2}{8} = \frac{1000.3(24')^2}{8} = 72 \text{ k·ft}$$

$$\phi_b M_n = 308.4\text{k·ft} > 72 \text{ k·ft } \underline{\text{OK}}$$

AISC Table 1-1 → $I_x = 340 \text{ in}^4$ for W14×34

$$\Delta = \frac{M_u L^2}{c\, I_x} = \frac{72\,(24')^2}{161\,(340)} = 0.76'' < 0.8'' \quad \underline{\underline{\text{OK}}}$$

$$\frac{72\,(19.33)^2}{161\,(340)} = 0.49'' < 0.64'' \quad \underline{\underline{\text{OK}}}$$

Beam Size	Nominal Shear Capacity (kips)
W8X10, W10X12	15
W8X13, 15, W10X15	25
W8X18, 21, 24, W10X17, 19, 22, 26	30
W8 ≥ 28, W10 ≥ 30	35
W12X14, 16	35
W14 ≤ 30, W12X19, 22, 26, 30	40
W12X35, 40, 45, W14X34, 38, 43, 48	55
W12 ≥ 50, W14 ≥ 53	65
W16X26, 31	60
W16X36, 40, W18X35, W18X40	75
W16 ≥ 45, W18X46, 50, 55	85
W18 ≥ 60, W21 ≤ 62, W24X55	110
W21 ≥ 68, W24X62, 68, 76	130
W24 ≥ 84, W27X84	155
W27 ≥ 94, W30X99	195
W30 ≥ 108	230
W33	260
W36	290

W12, W14	35
W16, W18	60
W21, W24	75
W27, W30	90
W33, W36	110

	E-M1	N1	E7	F7	G7	H7	J7	K7	L7	M7	N7
Roof	2 HSS 16x8x3/8	HSS 16x8x3/8									
	W14x22 - 40	W14x22 - 40									
		HSS 16x8x5/8									
Roof Framing Plan	2 W24x55 - 220	W33x18 BF2 - 110	W24x55 - 110	W24x76 - 130	W24x62 BF4 - 75	W24x62 - 130	W24x55 - 110	W24x55 BF5 - 75	2 W24x55 - 220	W24x55 - 110	W24x55 BF6 - 75
	TR1A - 110	TR2 - 100	W24x76 -130	W24x62 BF4 -75	W24x62 - 130	W24x55 - 110	W24x55 BF5 - 75	W24x55 - 110	W21x44 - 130	W24x55 BF6 - 75	W33x118 - 260
		W24x55 - 110	TR1A - 110	TR1A - 110	T1A - 110	TR1A - 110	W12x19 - 40	W16x31 - 60	TR1A - 110	W16x26 - 60	W14x22 - 40
							TR1A - 110	TR1A - 110		TR2 - 100	TR2 - 100
5th Floor	2 HSS 12x8x3/8	W18x40 BF2 - 60	2 W18x35 - 150	W18x35 - 75	W18x40 BF4 - 60	2 W18x35 - 150	W18x35 - 75	W18x40 BF5 - 60	2 W18x35 - 150	W18x35 - 75	W18x40 BF6 - 60
	W10x19 - 30	W10x19 - 30	W10x19 - 30	W10x19 - 30	W10x19 - 30	W10x19 - 30	W10x19 - 30	W10x19 - 30	W10x19 - 30	W18x40 BF6 - 60	W18x50 - 85
		HSS 12x8x3/8		W18x40 BF4 - 60	W18x35 - 75		W18x40 BF5 - 60	W18x35 - 75	W21x44 - 130	W16x26 - 60	W10x19 - 30
							W12x19 - 40	W16x31 - 60		W10x19 - 30	W14x22 - 40
4th Floor				HSS 7x7x1/2 BF4	HSS 7x7x1/2 BF4		HSS 7x7x1/2 BF5	HSS 7x7x1/2 BF5		HSS 7x7x1/2 BF6	HSS 7x7x1/2 BF6
Total Load (kips)	400	450	530	480	480	530	540	580	770	570	690

ALTERNATIVE 1

FREE STANDING FRAME SYSTEM W/ I-BEAM

CONSERVATIVE APPROACH → ASSUME EFFECTIVE WIDTH = 24 FT

LOADS:

CONCRETE = $\left[(145 \text{ PCF} \times 6''/12'') - \underbrace{2.84 \text{ PSF}}_{\text{steel decking}}\right] \times 1.1 \times 24' = 1839$ lb/ft

DECKING = 2.84 PSF × 24' = 68.16 lb/ft

MEP + CEILING = 15 PSF × 24' = 360 lb/ft

GIRDER (FROM FLOOR SYSTEM) = 34 lb/ft

TOTAL DEAD LOAD = 2.301 k/ft

LL = 100 PSF × 24' = 2.4 k/ft

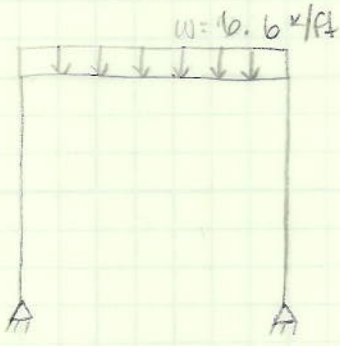
$w_u = 1.2D + 1.6L = 1.2(2.301) + 1.6(2.4) = 6.6$ k/ft

$P = 6.6 \text{ k/ft} \times \underbrace{107.33 \text{ ft}}_{\text{Length}} = 708.38$ K

USING AISC STEEL MANUAL TABLE 3-6:

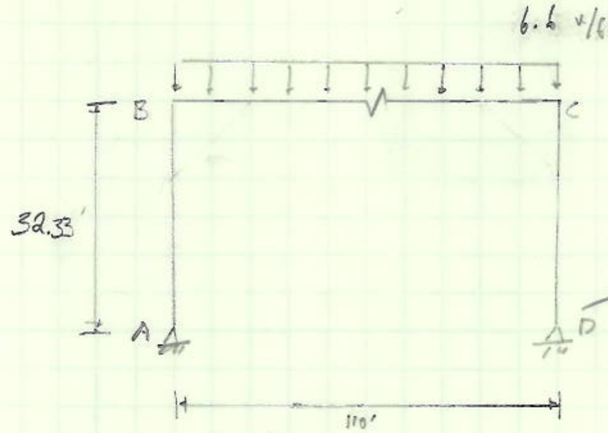
TRY W27 × 94 → uniform load (kips) @ 10' span

= 791 K > 708.38 K



CHECK MOMENT

AND WEIGHT OF GIRDER

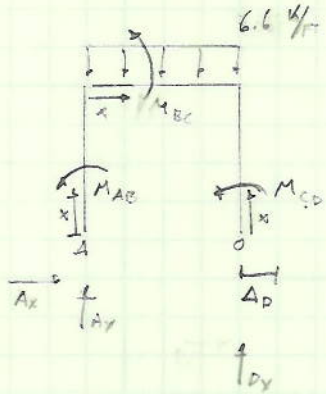


STATICALLY INDETERMINATE 1°
4 reactions − 3 equations

FORCE METHOD OF ANALYSIS

→ REPLACE W/ROLLER

EI CONSTANT



$\xrightarrow{+} \sum F_x = A_x = 0$

$A_x = 0$

$+\uparrow \sum F_y = A_y - 6.6 \times 107.33 + D_y =$

$A_y = D_y = 354.11^k$

TOTAL DISTRIBUTED LOAD
= 3862.5 lb/ft

$E = 29 \times 10^6$ PSI (29000 KSI)

$I_{BC} = 510 \text{ IN}^4$

4176000 K/F

W 18 × 35

$\circlearrowright \sum M_{AB} = M_{AB} + [A_x(x) = 0] = 0$

$M_{AB} = 0$

$I_{BA} = 999 \text{ IN}^4 = I_{CD}$

W14 × 90

$\circlearrowright \sum M_{BC} = 0 = M_{BC} - 354x + \frac{6.6x^2}{2}$

$M_{BC} = -3.3x^2 + 354x^2$

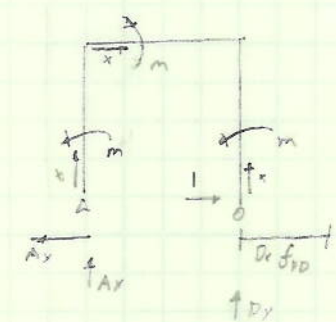
$999 \text{ IN}^4 \times \frac{1 \text{ FT}^4}{20736}$

0.048177

$\circlearrowright \sum M_{CD} = 0 = M_{CD}$

$M_{CD} = 0$

$\frac{510}{20736}$ 0.024595



$\sum F_x = 0 = 1 + A_x$

$A_x = 1$

$\sum F_y = 0 = A_y + D_x$

$A_y = 0 = D_y$

$\frac{K}{IN^2} \times \frac{144 \text{ IN}^2}{1 \text{ FT}^2}$

$\circlearrowright \sum M_{AB} = m_{AB} - 1x$

$m_{AB} = x$

$\sum M_{BC} = +m_{BC} - 32.33x$

$m_{BC} = 32.33x$

$\sum M_{CD} = m_{CD} + 1x$

$m_{CD} = -x$

$$\Delta_D = \int_0^L \frac{mM}{EI}dx = \cancel{\int_0^{32.33} \frac{x(0)}{EI}}^{\,0} + \int_0^{110} \frac{32.33x(-3.3x^2 + 354x)}{EI_{BC}} + \cancel{\int_0^{32.33} \frac{-x(0)}{EI}}^{\,0}$$

$$= \int_0^{107} \frac{-106.69x^3 + 11450.93x^2}{EI_{BC}}$$

$$f_{DD} = \int_0^{L} \frac{m^2}{EI} = \int_0^{32.33} \frac{x^2}{EI_{AB}} + \int_0^{107.33} \frac{(32.33x)^2}{EI_{BC}} + \int_0^{32.33} \frac{(-x)^2}{EI_{CD}}$$

$$(\xrightarrow{+})\quad \Delta_D + f_{DD}\,D_x = 0 \qquad = \int_0^{32.33} \frac{x^2}{EI_{AB}} + \int_0^{107.33} \frac{1045.23\,x^2}{EI_{BC}} + \int_0^{32.33} \frac{x^2}{EI_{CD}}$$

$$f_{DD} = \int_0^{33.5} \left(\frac{x^2}{EI_{AB}} + \frac{x^2}{EI_{CD}}\right) + \int_0^{107.33} \frac{1122.25x^2}{EI_{BC}}$$

$$\int_0^{107.33} \frac{-106.69x^3 + 11450.93\,x^2}{EI_{BC}} + \left[\int_0^{32.33} \left(\frac{x^2}{EI_{AB}} + \frac{x^2}{EI_{CD}}\right) + \int_0^{107.33} \frac{1045.23\,x^2}{EI_{BC}}\right] D_x = 0$$

W40×593

$I_{BC} = 50400\ \text{IN}^4 \times \frac{1\ \text{FT}^4}{20736\ \text{IN}^4} = 2.43\ \text{FT}^4$

W 14×90

$I_{BA} = I_{CD} = 999\ \text{IN}^4 \times \frac{1\ \text{FT}^4}{20736\ \text{IN}^4} = 0.0482\ \text{FT}^4$

$E = 29\times10^6\ \text{psi}$

$29000\ \text{KSI} \cdot \frac{144\ \text{IN}^2}{1\ \text{FT}^2} = 4176000\ \text{KSF}$

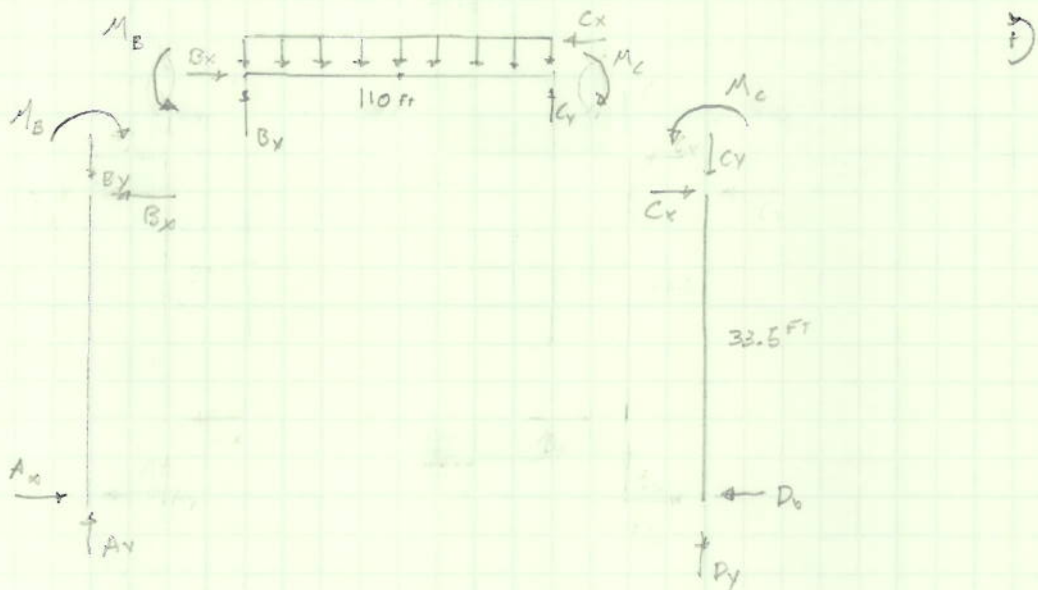
$$0 = \Big|_0^{107.33} \left[\frac{-106.69x^4}{4EI_{BC}} + \frac{11450.93x^3}{3EI_{BC}}\right] + \left[\Big|_0^{32.33} \left[\frac{x^3}{3EI_{AB}} + \frac{x^3}{3EI_{CD}}\right] + \Big|_0^{110} \frac{1045.23\,x^3}{3EI_{BC}}\right] D_x$$

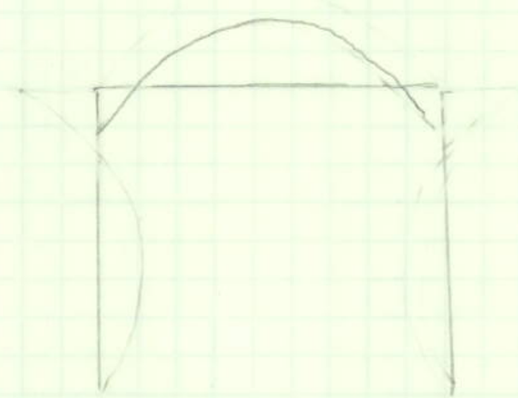
$$\left[-\frac{106.69\,(107)^4}{4EI_{BC}} + \frac{11450.93\,(107)^3}{3EI_{BC}}\right] - 0 + \left[\left[\frac{(32.33)^3}{3EI_{AB}} + \frac{(32.33)^3}{3EI_{CD}}\right] - [0+0] + \frac{1045.23\,(107)^3}{3EI_{BC}}\right] D_x = 0$$

$$\frac{-3.9\times10^9}{EI_{BC}} + \left[\frac{11285}{EI_{AB}} + \frac{11285}{EI_{CD}} + \frac{4.64\times10^8}{EI_{BC}}\right] D_x = 0$$

$$D_x = \frac{-\dfrac{3.9\times10^9}{EI_{BC}}}{\left[\dfrac{11285}{EI_{AB}} + \dfrac{11285}{EI_{CD}} + \dfrac{4.64\times10^8}{EI_{BC}}\right]} = \frac{-\dfrac{3.9\times10^9}{\cancel{E}(2.43)}}{\dfrac{11285}{\cancel{E}(0.0482)} + \dfrac{11285}{\cancel{E}(0.0482)} + \dfrac{4.24\times10^8}{\cancel{E}(2.43)}}$$

$D_x = -840''$





$D_x = -8.4\ K$

$\sum F_x = 0 = A_x - 8.4$

$A_x = 8.42^k$

$\sum F_y = -6.6\,(107.33) + A_y + D_y$

$A_y = D_y = \frac{6.6 \times 107.33}{2} = 354\ K$

$B_y = A_y = 354\ k = C_y$

$B_x = A_x = 8.4 = C_x$

$\circlearrowright \sum M_B = 0 = 8.4 \times 32.33 - M_B$

$M_B = 271.7$ Ft-Kips $= M_C$

$A_x = 8.40^k$

$A_y = 363^k$

$B_x = 8.40^k$

$B_y = 363^k$

$M_B = 271.7$ Ft-Kips

$C_x = 8.4^k$

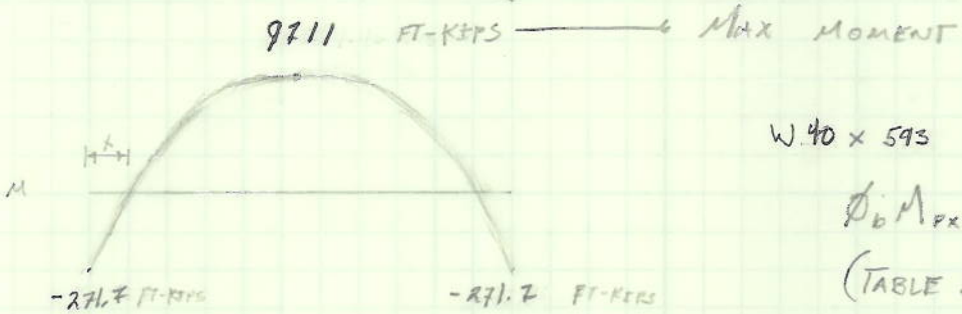
$C_y = 363^k$

$M_C = 271.7$ Ft-Kips

$D_x = 8.4^k$

$D_y = 363^k$

Beam BC



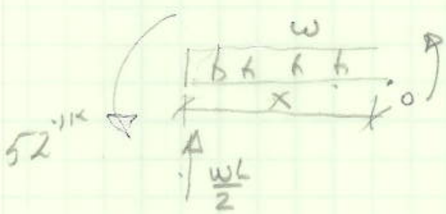
W.40 × 593

$\phi_b M_{px} = 10400$ kip-FT

(TABLE 3-2)

$\frac{x}{52.26} = \frac{55}{5710.87}$

$x = 0.5$ Ft



$M_o = 0$?

$(M_o = 0) + 52'^{K} - \frac{\omega L}{2} x + \frac{\omega x^2}{2} = 0$

$0 + 52 - 212x + \frac{3.85x^2}{2} = 0$

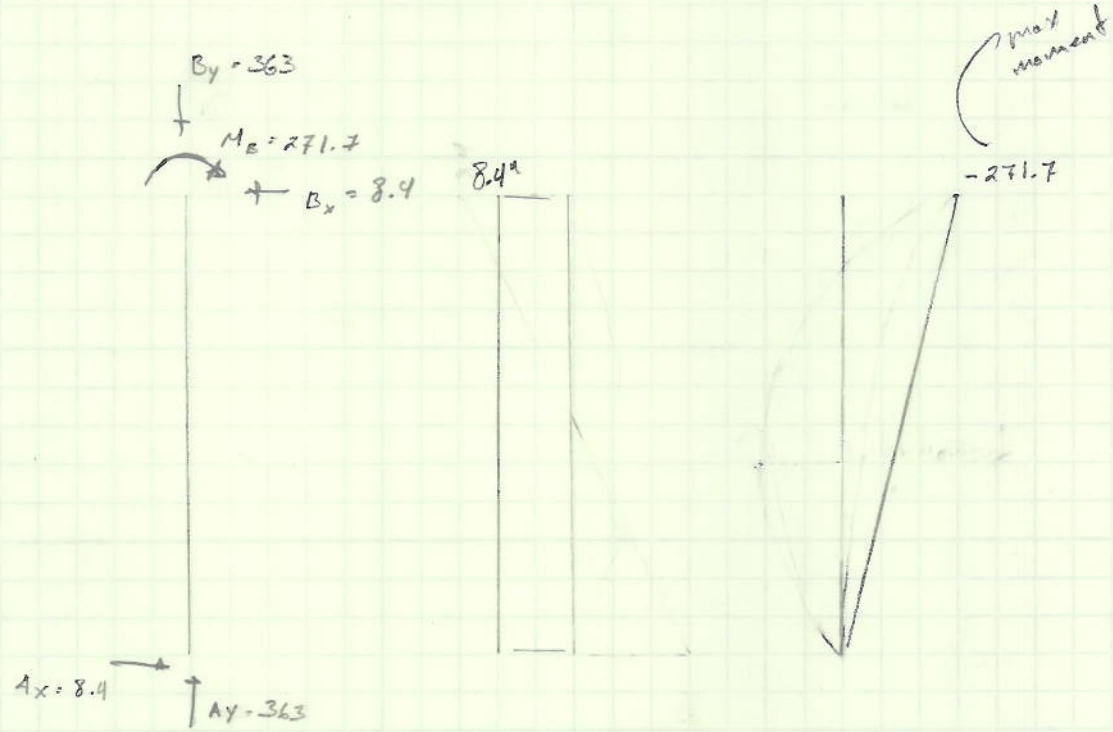
1.925

$0 + 271.7 - 363x + \frac{6.6x^2}{2} = 0$

3.3

→ GRAPH

Still → = 0 when x = 0.75 FT



W14 x 90 Allowable Moment = 573 FT-KIPS

TABLE 3-2

ADEQUATE GIRDER = W40 × 593

CHECK LOADS WITH GIRDER WEIGHT

DEAD LOAD = 2.301 k/ft + 0.593 k/ft = 2.894

↳ beam weight

LIVE LOAD = 2.4 k/ft

$w_u = 1.2D + 1.6L = 1.2(2.894) + 1.6(2.4) = 7.3 \text{ k/ft}$

$P_u = 7.3 \text{ k/ft} \times 107.33 = 783.5^k$

↳ Length

$P_u = 783.5^k$ is acceptable for W40 × 593

$V_u = \dfrac{783.5^k}{2} = 391.75^k$

FREE STANDING I-BEAM FRAME COLUMN DESIGN

Length = $\frac{110}{2}$

LIVE LOAD – 100 PSF × 24 LF × 55 LF = 132 ^{K}

DEAD LOAD:

ponding

CONCRETE = $[(145 \text{ PCF} \times 6''/12'') - 2.84] \times 1.1 \times 24 \times 55 = 101.1^K$

MEP + CEILING = 15 PSF × 24 × 55 = 19.8 ^{K}

DECKING = 2.84 PSF × 24 × 55 = 3.7 ^{K}

GIRDER = 34 PLF × 55 = 1.9 ^{K}

FRAME GIRDER = 593 PLF × 55 = 32.6 ^{K}

TOTAL DL = 159.1 ^{K}

LOAD COMBINATION → $1.2D + 1.6L = 1.2(159.1) + 1.6(132)$

$P_u = 402.12^K + 770^K$ (from above floors, see spreadsheet) $= 1172^K$

GRAVITY SYSTEM, assume $KL = (1.0)(32.33') = 32.33'$

TRY W14 × 90 → $[\phi_c P_n = 481.5^K, r_y = 3.7'', r_x = 6.14'', A_g = 26.5 \text{ in}^2]$

interpolated

Table 4-1

$r_y < r_x \therefore \frac{KL}{r}$ is governed by r_y

$$\frac{KL}{r_y} = \frac{(1.0)(32.33' \times 12'')}{3.7''} = 104.85$$

$$\frac{32.33 - 32}{34 - 32} = \frac{x}{1200 - 1100}$$

$= 16.667$

$$\lambda_c = 4.71\sqrt{\frac{E}{F_y}} = 4.71\sqrt{\frac{29{,}000 \text{ ksi}}{50 \text{ ksi}}} = 113.43$$

$KL/r = 104.85 < \lambda_c = 113.43$ ∴ COLUMN IS SHORT AND NON-SLENDER

$$F_e = \frac{\pi^2 E}{(L/r)^2} = \frac{\pi^2 (29000)}{(104.85)^2} = 26.04 \text{ Ksi}$$

$$F_{CR} = [0.658^{F_y/F_e}]F_y = [0.658^{50/26.04}]50 = 22.4 \text{ Ksi}$$

VERIFY AXIAL CAPACITY

$$\phi_c P_n = \phi_c F_{CR} A_g = 0.9(22.4)(26.5) = 533.78^K$$

$$\phi_c P_n = 533.78^K > P_u = 402.12^K \text{ OK}$$

USE W14 × 90

COLUMN HEIGHT: 32'-4"

ALTERNATIVE 1 - CONNECTIONS

GIRDER TO COLUMN CONNECTION

- DOUBLE ANGLE CONNECTION
- ANGLE STEEL : A36 ($F_y = 36$, $F_u = 58$)
- ANGLE SIZE : TRY $2L\,3\tfrac{1}{2} \times 3\tfrac{1}{2} \times t$
- ASSUME 1" BOLTS → A325-N

Determine required # of bolts :

$$A_b = \frac{\pi d^2}{4} = \frac{\pi (1)^2}{4} = 0.7854 \text{ in}^2$$

AISC T. J3.2

$$\phi R_n = 2\phi F_y A_b = 2(\phi = 1")(F_y = 48 \text{ ksi})(A_b = 0.7854) = \underline{75.398 \text{ k/bolt}} \text{ in double shear}$$

$V_u = 387.5^k$ (see column and girder design)

Check shear resistance , $V_n = 0.6 F_y A_w$

$A_w = d t_w = (43)(1.79) = 76.97$ → AISC T.1.1 For W40×593

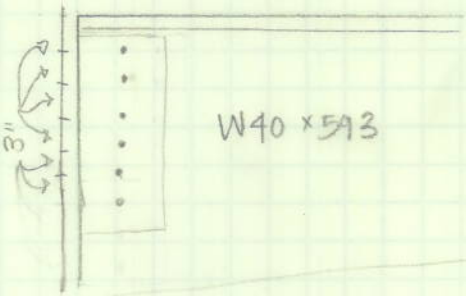
$$\phi V_n = 0.6(50)(76.97) = 2309.1^k > 387.5^k \quad \underline{OK}$$

BOLTS

$$N = \frac{V_u}{\phi R_n} = \frac{387.5^k}{75.398} = 4.8 \rightarrow \underline{\text{use 6 bolts}}$$

Establish connection geometry:

W40×593 → T = 34"   T/2 = 17"



min. → T.J3.4

For 1"ϕ bolts, $1\tfrac{3}{4}$" at sheared edges

$$TOTAL = 2(1\tfrac{3}{4}") + \underbrace{15"}_{3" \times 5 \text{ gaps}} = 18.5" = L$$

$$T/2 = 17" \le L = 18.5" \le T = 34" \quad \underline{OK}$$

provide lateral bracing

Appendix 6   A-6-7 (equ)
M_r / h_o = force in truss
Transfer 10 kips

angles - smaller stick out

- length of angle + other way [

Table J2.5

- T/2 < T

size of weld × 0.707 effective throat
area = length × ϕ = \$
ϕ × that (x) strength = 70 ksi
how much leg to we need?

Establish angle thickness by investigating strength limit states

① Bolt Bearing Capacity - Tear out

$\phi R_n = \phi 1.2 \overset{\text{TEAR OUT}}{L_c t F_u} \leq \overset{\text{BEARING}}{\phi 2.4 d_b t F_u}$ $L_c = 1\frac{3}{4}" - \frac{1}{2}(1" + \frac{1}{8}") = 1.1875$

TEAR OUT: $(1)(1.2)(1.1875")(58\,ksi)t = 82.65t$

BEARING: $(1")(2.4)(1")(58\,ksi)t = 139.2t$

TEAR OUT GOVERNS $\rightarrow$ TOTAL CAPACITY $= 6(82.65t) = 495.9t$

$2(495.9t$ per angle$) = 991.8t^k > 387.5^k$

$t \geq 387.5/991.8 = 0.391"$

② Angle Shear Rupture

$\phi R_n = 2\phi 0.6 F_u (L - n d_e)t$
$= 2(1)(0.6)(58)[18.5" - 6(1" + \frac{1}{8}")]t \geq 387.5^k$

$817.8t \geq 387.5^k \rightarrow t = 0.474"$

③ Angle Shear Yield

$\phi R_n = 2\phi 0.6 F_y L t \geq 363^k$
$= 2(1)(0.6)(36)(18.5)t > 387.5$
$= 1287.6t > 387.5^k \rightarrow t = 0.3"$ GOVERNS

GOVERNING THICKNESS $t = 0.474" \rightarrow$ use $t = \frac{1}{2}"$

CHECK BEARING ON GIRDER WEB

$\phi R_n = \phi 1.2 L_c t F_u \leq \phi 2.4 d_b t F_u$

$\phi 1.2 L_c t F_u = 1(1.2)(1.1875)(t_w = 1.79")(F_u = 65\,ksi) = 165.8$

$\phi 2.4 d_b t F_u = 1(2.4)(1)(1.79")(65) = 279.24$

$6(165.8) = 994.8^k > V_u = 387.5^k$ OK

$\boxed{\text{use } 2L\ 3\frac{1}{2} \times 3\frac{1}{2} \times \frac{1}{2}}$

$\boxed{L = 24.5"}$

COLUMN TO CONCRETE W/ BASE PLATE CONNECTION

- EXISTING CAST-IN-PLACE PIER AT COLUMN BASE (72" × 42")

COLUMN SIZE: W14×90 ($d = 14"$, $b_f = 14.5"$, $F_y = 50$ ksi)

CONCRETE PIER: $f'_c = 4000$ psi $= 4$ ksi (CANNON S001)

BASE PLATE: ASTM A-36 GRADE 42 (CANNON S001) $F_y = 36$ ksi

$P_u = 402.12^K$ (SEE ALT. 1 COLUMN DESIGN) $\phi_c = 0.6$

DETERMINE AREA OF BASE PLATE (assume $\sqrt{A_2/A_1} = 2$)

$$A_1 = \frac{P_u}{\phi_c(0.85f'_c)\sqrt{A_2/A_1}} = \frac{402.12}{0.6(0.85(4))(2)} = 98.56 \text{ in}^2$$

$b_f d = 14.5" \times 14" = 203 \text{ in}^2 > 98.56 \text{ in}^2$ NO GOOD

$A_1 =$ USE AT LEAST 203 in^2 BASE PLATE

OPTIMIZE BASE PLATE DIMENSIONS

$$\Delta = \frac{0.95d - 0.8b_f}{2} = \frac{0.95(14) - 0.8(14.5)}{2} = 0.85"$$

$N = \sqrt{A_1} + \Delta = \sqrt{203} + 0.85 = 15.1$, say 16"

$B = \frac{A_1}{N} = \frac{203}{16} = 12.7$, say 16" to be conservative and square

SQUARE PLATE → 16" × 16" ($B = N = 16"$)

CHECK BEARING → $\phi_c P_p = \phi_c 0.85 f'_c A_1 \sqrt{\frac{A_2}{A_1}}$

PIER AREA = 42" × 42" or 42" × 72"
$A_2 = 1764$ or 3024, $\sqrt{A_2/A_1} = 2.625$ or 3.43, respectively

$\phi_c P_p = 0.6(0.85)(4)(256)(2.625) = 1370.88^K > 402.12^K$ OK
$\phi_c P_p = 0.6(0.85)(4)(256)(3.43) = 1791.2^K > 402.12$ OK

PLATE THICKNESS

$m = (N - 0.95d)/2 = (16 - 0.95(14))/2 = 1.35"$

$n = (B - 0.8b_f)/2 = (16 - 0.8(14.5))/2 = 2.2"$

$\lambda n' = \sqrt{db_f}/4 = \sqrt{(14.5)(14)}/4 = 3.56"$ GOVERNS

$l = 3.56''$

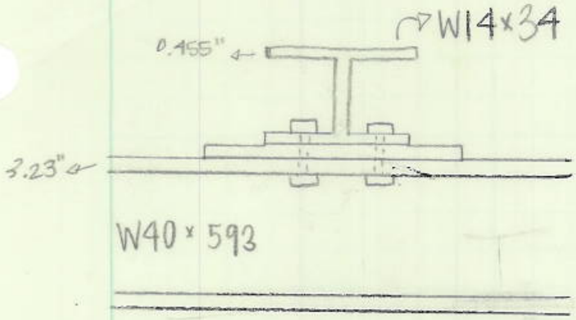
$t_{reqd} = l\sqrt{\frac{2P_u}{0.9F_y BN}} = 3.56\sqrt{\frac{2(402.12)}{0.9(36)(256)}} = 1.1$, use $1.5''$

use PL 1.5 × 16 × 16 in A36 w/ existing pier

SINCE ALT. 2 HAS $P_u = 370.2^K < 402.12^K$,
AND W14×90, SAME BASE PLATE DESIGN
CAN BE USED FOR ALT. 2.

fillet weld to column
anchor rods in concrete raise to base plate
grout

FLOOR SYSTEM BEAMS TO GIRDER CONNECTION



- Base plate and bolts provide lateral bracing for girder.
- System must be rigid

In AISC Steel Manual, Appendix 6 - STABILITY BRACING

For Nodal Bracing:

Equ (A-6-7) — $P_{br} = 0.02 M_r C_d / h_o = 0.02(1226^k)$

$= \underline{24.52^K}$ *Assume $C_d = 1$

Bolts must transfer 24.52^K

- BOLTED THROUGH PLATE AND BOTH FLANGES
- PLATE STEEL: A-36 $F_y = 36$ ksi, $F_u = 58$ ksi
- PLATE SIZE: ASSUME 1" PLATE (t_f(girder) > 1" > t_f(beam))
- ASSUME 3/4" BOLTS → A325-N

Determine # of bolts:

$A_b = \frac{\pi d^2}{4} = \frac{\pi(3/4)^2}{4} = 0.4418 \text{ in}^2$

$\phi R_n = 2\phi F_y A_b = 2(3/4)(48 \text{ ksi})(0.4418) = 31.8$ K/bolt in double shear

AISC. TJ3.2 → WOULD THIS BE A BEARING CONNECTION OR TENSILE

Shear force acting on girder through beam is 6.6 K/ft × trib width of beams = 10' = $66^K = V_u$

Check Shear Resistance, $V_n = 0.6 F_y A_w$

$A_w = d t_w = (14)(0.285)$ FOR W14 × 34 = 3.99

$V_n = 0.6(50)(3.99) = 119.7^K > 66^K$ OK

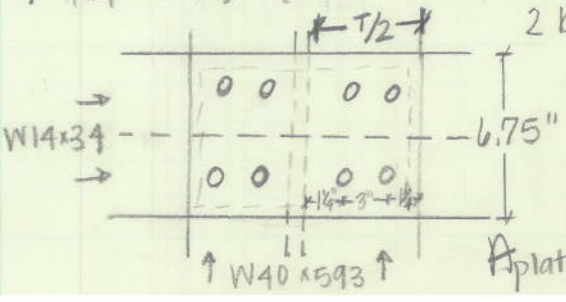
$\# \text{BOLTS}(N) = \frac{V_u}{\phi R_n} = \frac{66}{31.8} = 2.07$ → use 4 bolts

$T = (b_f = 16.7") - (t_w = 1.79") = 14.91"$ $T/2 = 7.455"$ ∴ 2 bolts $L < T/2$

For 3/4" bolts, 1¼" at sheared edges T.J3.4

3" between bolts

TOTAL L = [2(1¼") + 3"] × 2 sides = 11"



$T/2 = 7.455 \le L = 11.0" \le 14.9"$ OK

$A_{plate} = b_f(\text{girder}) = 16.7" \times b_f(\text{beam}) + 2"$ (1" on each side) = 8.75"

ALTERNATIVE 2

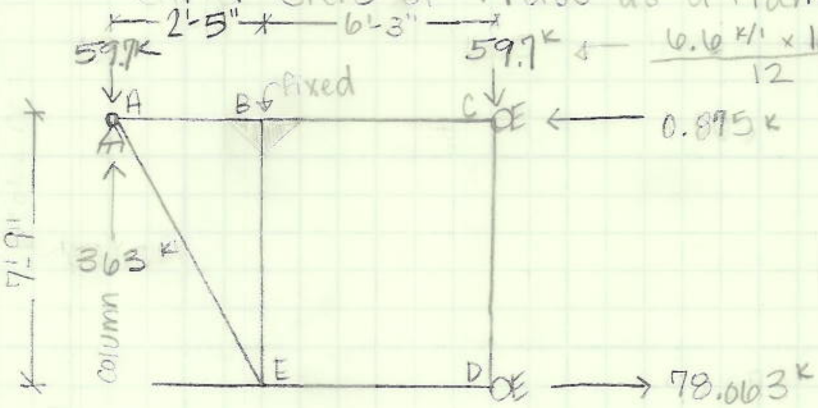
FREE STANDING TRUSS DESIGN

GEOMETRY CONSTRAINTS:

- Duct runs through existing precast arches and will run through truss system.
  - Duct is circular w/ diameter = 5'-6"
- Floor system girders above truss will act as point loads on truss. Therefore vertical members of truss must match locations of girders (10' O.C.)

ANALYSIS:

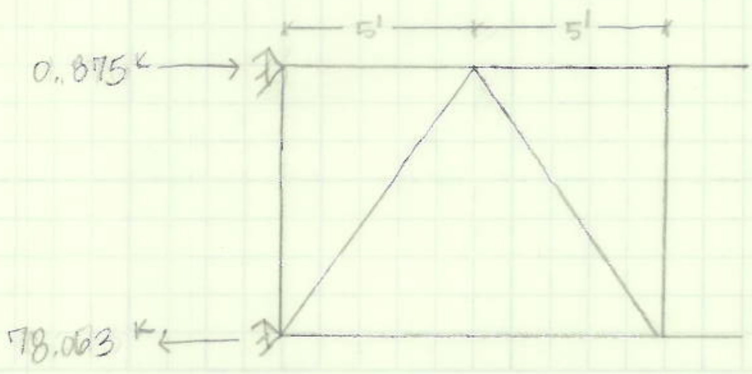
- use RISA software and reaction forces obtained from the Free Standing I-beam Design.
- since truss must allow duct, treat first 10' on either side of truss as a frame analysis.



*Reactions obtained using RISA.

RISA spreadsheets and drawings on following page.

- Must assume that column is pin connected to truss, joint B is fixed rather than pin connected to resist moment and frame is connected by rollers to remainder of truss.
- Analyze truss from frame system to center line using reactions obtained from frame analysis.



TOTAL LENGTH OF ALT 2 TRUSS = 107'-4"

DESIGN:

TOP + BOTTOM CHORDS
↳ MOMENT + BENDING CAPACITY GOVERN

$$M_u = \frac{\frac{wL^2}{8}}{h = 7.75'} = \frac{\frac{(6.6^{k}/ft)(108.96')^2}{8}}{h = 7.75} = 1252 \text{ kips}$$

- use similar system to truss in gymnasium w/ top and bottom chords as WT shapes and web members as double angle shapes.
- using Table 4-7 and $\phi_c P_n > 1252^k$, try WT12×114.5
  - ↳ $F_y = 50$ ksi
  - ↳ $\phi_c P_n$ @ effective length = 10' = 1390 K

DIAGONAL
WEB MEMBERS

- Max axial force is in outside web member. From RISA, max axial force = 287.994 K
- using Table 4-9 and $\phi_c P_n > 287.994^k$, try 2L6×4×5/8
  - ↳ $F_y = 36$ ksi
  - ↳ $\phi_c P_n$ @ effective length ≈ 10' = 307 K
- half of the members have an axial force of 143.997 K. For these members, try 2L5×3×7/16
  - ↳ $F_y = 36$ ksi
  - ↳ $\phi_c P_n$ @ effective length ≈ 10' = 159 K

VERTICAL MEMBERS

- Max axial force is found to be 257.5 ~~33~~^{k} in outside vertical member
- using Table 4-9, try 2L6×4×5/8
  - ↳ $F_y = 36$ ksi
  - ↳ $\phi_c P_n$ @ effective length ≈ 8' = 332^k

CHECK COLUMN AND LOADS W/ WEIGHT OF TRUSS

WEIGHT OF TRUSS = 44^k

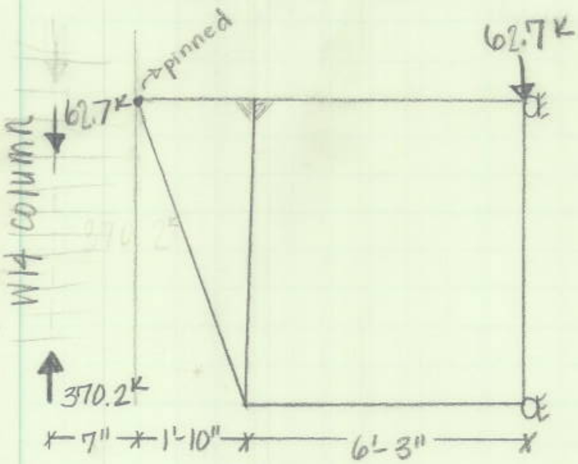
(REFER TO SPREADSHEET FOR VALUE DEFINITIONS)

$$6.6\ ^k/_1 \times 107.33' = 708.4^k$$

$$708.4^k + 44^k = 752.4^k$$

$$\frac{752.4^k}{12 \text{ GIRDERS}} = 62.7^k \rightarrow$$ CHECK IN RISA TO ENSURE MEMBER SIZES ARE ADEQUATE.

COLUMN FORCE IS NOW 370.2^k



$$V_u = \frac{6.6\ ^k/ft \times 107.33ft}{2} = 354.2^k$$

TOP + BOTTOM CHORDS

↳ MOMENT + BENDING CAPACITY GOVERN

$$M_u = \frac{\frac{wL^2}{8}}{h=7.75'} = \frac{\frac{\left(\frac{752.4^k}{107.33'}\right)(107.33')^2}{8}}{h=7.75'} = 1302.5^k$$

$M_u = 1302.5^k < 1390^k$ OK

$\boxed{\text{USE WT } 12 \times 114.5}$

DIAGONAL WEB MEMBERS

- max axial force is in outside web member. From RISA, max axial force = 300.925^k

$2L6 \times 4 \times 5/8$, $\phi_c P_n = 307^k > 300.925^k$ <u>OK</u>

- half of the members have an axial force of 150.462^k.

$2L5 \times 3 \times 7/16$, $\phi_c P_n = 159^k > 150.462^k$ <u>OK</u>

VERTICAL MEMBERS

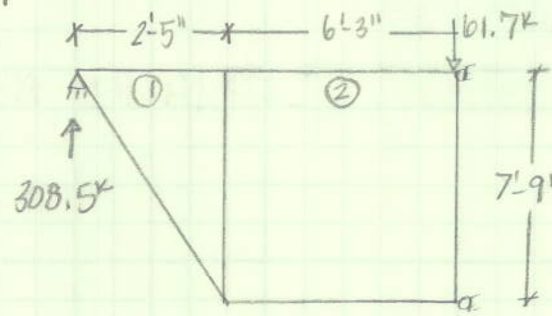
- max axial force is in outside vertical member. From RISA, max axial force = 269.319^k

$2L6 \times 4 \times 5/8$, $\phi_c P_n = 332^k > 269.319^k$ <u>OK</u>

All truss member sizes are adequate.

ALT. 2

Top chord of Frame



RISA ANALYSIS → member ① axial force = 36^K

Using T.4.8 (AISC Manual) Try 2L 3×3×7/16

$KL = 2.417 \quad \phi_c P_n = 152^K @ 2'$

$\phi_c P_n = 145^K @ 3'$

$\frac{2.417 - 2}{3 - 2} = \frac{x}{152 - 145} \qquad \phi_c P_n @ 2.417' = 149^K > 36^K$ OK

RISA ANALYSIS → member ② max moment = 386^K

Using T.3.2 (AISC Manual) Try W18×175

$\phi_c M_{px} = 498^{1K} > 386^{1K}$ OK

FREE STANDING TRUSS
COLUMN DESIGN

LIVE LOAD = 100 PSF × 24 LF × 53.665 = 129^K

DEAD LOAD:
CONCRETE = [(145 PCF × 6"/12") − 2.84] × 1.1 × 24 × 53.665 98.7 ^{K}
MEP + CEILING = 15 PSF × 24 × 53.665 = 19.3 ^{K}
DECKING = 2.84 PSF × 24 × 53.665 3.65 ^{K}
GIRDER = 34 PLF × 53.665 = 1.8 ^{K}
TRUSS = $33^K/2$ = 16.5 ^{K}

TOTAL DL = 140^K

LOAD COMBINATION → $1.2D + 1.6L = 1.2(140) + 1.6(129)$

$P_U = 374.4^K$

GRAVITY SYSTEM, ASSUME $KL = (1.0)(32.33') = 32.33'$

TRY W14×90 → [$\phi_c P_n = 481.5^K$, $r_y = 3.7"$, $r_x = 6.14"$, $A_g = 26.5 IN^2$] TABLE 4-1
INTERPOLATED

$r_y < r_x \therefore \frac{KL}{r}$ IS GOVERNED BY r_y

$$\frac{KL}{r_y} = \frac{1.0(32.33' \times 12")}{3.7"} = 104.85$$

$$\lambda_c = 4.71\sqrt{\frac{E}{F_y}} = 4.71\sqrt{\frac{29000 KSI}{50 KSI}} = 113.43$$

$KL/r = 104.85 < \lambda_c = 113.43$ → COLUMN IS SHORT AND NON-SLENDER

$$F_e = \frac{\pi^2 E}{(L/r)^2} = \frac{\pi^2(29000)}{(104.85)^2} = 26.04 KSI$$

$$F_{CR} = [0.658^{F_y/F_e}]F_y = [0.658^{50/26.04}]50 = 22.4 KSI$$

VERIFY AXIAL CAPACITY

$\phi_c P_n = \phi_c F_{CR} A_g = 0.9(22.4)(26.5) = 533.78^K$

$\phi_c P_n = 533.78^K > P_u = 374.4^K$ OK

USE W14×90

Alternative 2 - Connections

- In order to connect top chord of truss to column replace "frame" section of top chord (outside sections) from a T beam (WT 12×114.5) to a double angle, similar to web members. Connect this and connecting diagonal double angle to a T-beam gusset, which will be bolted to column.
- According to RISA analysis, max axial force is 0.545^k; the max shear is 516.119^k in the top chord of the frame, & max moment is $385.621^{k \cdot ft}$

380 385

By designing for max shear (516.119^k) for member w/ $KL = 8'-1"$, TRY $2L\,8\times6\times3/4$ - $\phi_c P_n = 548^k$ (interpolated)
↳ T. 4-10 AISC Manual

$V_u = 374.4^k \le \phi V_n$

$\phi V_n = 0.6 F_y A_w \Rightarrow (0.6)(50\text{ ksi})(A_w) = 374.4^k / 2$ → double shear

$A_w \ge 6.24\text{ in}^2 = t_w \times L$ of T-beam

See spreadsheet for:

- # BOLTS REQUIRED
- REQUIRED LENGTH (L)
- REQUIRED THICKNESS OF T-BEAM GUSSET

TRY WT9×79 ($t_w = 0.81"$, $t_f = 1.44"$)

$A_w \ge 6.24\text{ in}^2$

$A_w = 18.5" \times 0.81" = 14.95\text{ in}^2 > 6.24\text{ in}^2$ - OK

Alternative 2 - Top chord + Gusset

- According to RISA analysis, axial force in member $= 38.474^{K}$. Double angle.

TRY 2L 3 × 3 × 7/16 , $KL = 1.833'$; $\phi_c P_n = 156$ @ 1'
$\phi_c P_n = 152$ @ 2'.

$$\frac{1.833-1}{2-1} = \frac{x}{156-152} \quad x = 3.332$$

$$156 - 4.167 = \underline{152.667^{K} = \phi_c P_n}$$

Diagonal member connecting to gusset = 2L 6 × 4 × 5/8

Diagonal member required weld length = 15"

Top chord member required weld length = 11"

ALTERNATIVE 2 | - CONNECTIONS |

TOP CHORD T-BEAM TO COLUMN

- DOUBLE ANGLE CONNECTION
- ANGLE STEEL : A36 (F_y = 36 KSI, F_u = 58 KSI)
- ANGLE SIZE : TRY 3×3×t
- ASSUME 1" BOLTS → A325-N

WT 12×114.5 — d = 13, k = 2.23

SEE EXCEL SHEET FOR DETAILS

COLUMN TO CONCRETE W/ BASE PLATE CONNECTION

- ALL PROPERTIES OF COLUMN AND CONCRETE ARE THE SAME AS ALT. 1
- $P_u = 374.4^k$ (SEE ALT. 2 COLUMN DESIGN)

SEE BASE PLATE DESIGN SPREADSHEET FOR DETAILS

ALTERNATIVE 2 WELDS

WELD TO T-BEAM

DIAGONAL WEB MEMBERS

WT 12 × 114.5

$t_w = 0.96^{IN}$ > ANGLE THICKNESS $t = 7/16^{IN}$

∴ USE $t = 7/16^{IN}$

M19 – M23

2L5 × 3 × 7/16

E70 ELECTRODES = 70 KSI

MIN SIZE OF WELD

AISC TABLE J2.4 – OVER 1/4 to 1/2, MIN = $3/16^{IN}$

MAX SIZE OF WELD

$t \geq 7/16^{IN}$ $a \leq t - 1/16^{IN} \rightarrow a \leq 7/16 - 1/16 = 6/16$

USE $a = 3/8^{IN}$ FILLET WELD $3/16^{IN} \leq a \leq 3/8^{IN}$

FILLET WELD CAPACITY

$t_e = 0.707a = 0.707\left(3/8\right) = 0.265^{IN}$

NOMINAL CAPACITY OF WELD METAL: $R_n = F_w t_e = 0.6\,F_{EXX}\,t_e$

$= 0.6\,(70\text{KSI})(0.265\text{IN})$

$= 11.13\ ^K/_{IN}$

BASE METAL STRENGTH: SHEAR YIELDING: $R_n = 0.6 F_y A_g$

$= 0.6\,(36\text{KSI})(t = 7/16^{IN}) = 9.45\ K/IN$ FOR SHEAR YIELDING

SHEAR RUPTURE $R_n = 0.6 F_u A_{nv}$

$= 0.6\,(58\text{KSI})(t = 7/16^{IN}) = 15.225\ ^K/_{IN}$ FOR SHEAR RUPTURE

DESIGN STRENGTH = $\phi R_n = 0.75\,(9.45\ ^K/_{IN}) = 7.09\ ^K/_{IN}$

ANGLE LIMIT STATES: YIELD ON GROSS AREA: $\phi F_y A_g = 0.9\,(36\text{KSI})(7/16'' \times 11') = 156\ K$

FRACTURE ON NET AREA: $\phi F_u A_e = 0.75\,(58\text{KSI})(7/16'' \times 11') = 209\ K$

∴ TARGET CAPACITY FOR WELD: $V_u = 150.462^K$

REQUIRED WELD LENGTH: $L_w = \dfrac{V_u}{\phi R_n} = \dfrac{150.46^K}{2\,(7.09\ ^K/_{IN})} = 10.61\ IN \rightarrow$ SAY 11^{IN}

↳ DOUBLE ANGLE

$\frac{T}{2} \leq L_w \leq T$, $5.34 \leq 10.61 \leq 10.77$

WELD TO T-BEAM: DIAGONAL WEB MEMBERS M18 - M15

WT 12 × 114.5 $\qquad$ (2L6 × 4 × 5/8)

$t_w = 0.96^{IN} >$ ANGLE THICKNESS $t = 5/8^{IN}$

$\therefore$ USE $t = 5/8''$

E70 ELECTRODES = 70^{KSI}

MIN SIZE OF WELD

AISC TABLE J2.4 - OVER 1/2 TO 3/4 MIN = 1/4

MAX SIZE OF WELD

$t \geq 5/8^{IN} \qquad a \leq t - 1/16^{IN} \longrightarrow a \leq 5/8 - 1/16 = 9/16^{IN}$

$1/4^{IN} \leq a \leq 9/16^{IN}$

USE $a = 9/16^{IN}$ FILLET WELD

FILLET WELD CAPACITY

$t_e = 0.707a = 0.707\left(9/16\right) = 0.398^{IN}$

NOMINAL CAPACITY OF WELD METAL: $R_n = F_w t_e = 0.6 F_{EXX} t_e$
$= 0.6(70)(0.398) = 16.70\ ^{K}/_{IN}$

BASE METAL STRENGTH: SHEAR YIELDING: $R_n = 0.6 F_y t$
$= 0.6(36)(5/8) = 13.5^{K}/_{IN}$ SHEAR YIELDING

SHEAR RUPTURE $R_n = 0.6 F_u t$
$= 0.6(58)(5/8) = 21.75^{K}/_{IN}$ SHEAR RUPTURE

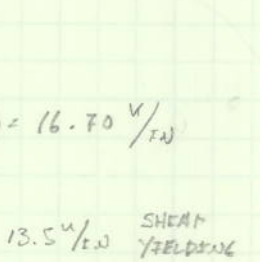
DESIGN STRENGTH = $\phi R_n = 0.75(13.5) = 10.125\ ^{K}/_{IN}$

ANGLE LIMIT STATES: YIELD ON GROSS AREA: $\phi F_y A_g = 0.9(36)(5/8'' \cdot 16'') = 324^{K}$

FRACTURE ON NET AREA $\phi F_u A_e = 0.75(58)(5/8'' \cdot 16'') = 433^{K}$

$\therefore$ TARGET CAPACITY FOR WELD $V_u = 300.925^{K}$

REQUIRED WELD LENGTH: $L_w = \dfrac{V_u}{\phi R_n} = \dfrac{300.925}{2(10.125)} = 14.86^{IN}$ SAY: 15^{IN}



$\frac{T}{2} \leq L_w\, 6T \longrightarrow 5.34 \leq 14.86 \not\leq 10.77$

WELD TO T-BEAM: VERTICAL MEMBERS 2L 6 x 4 x 5/8

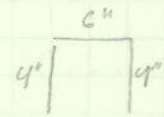
ANGLE LIMIT STATES:

1) YIELD ON GROSS AREA

$$\phi F_y A_g = 0.9(36)\left(5/8" \cdot 14^{IN}\right) = 283.5^{k}$$

2) FRACTURE ON NET AREA

$$\phi F_u A_e = 0.9(58)\left(5/8" \cdot 14^{IN}\right) = 456.75^{k}$$



∴ TARGET CAPACITY FOR WELD $V_u = 269.319^{k}$

REQUIRED LENGTH $L_w = \dfrac{V_u}{\phi R_n} = \dfrac{269.319}{2(10.125)} = 13.30^{IN} \rightarrow$ SAY 14^{IN}

$$5.39^{IN} \le 13.30 \not\le 10.77^{IN}$$

WELD TO DOUBLE ANGLE: DIAGONAL WEB MEMBER

$\angle$ 2L8x6x3/4 $\quad\quad$ $\angle$ 2L6x4x5/8

2L8x6x3/4

$t_w = 3/4^{IN}$ > ANGLE THICKNESS $t = 5/8^{IN}$

$\rightarrow$ USE $5/8^{IN} = t$

E70 ELECTRODES - 70^{KSI}

MIN SIZE OF WELD $\rightarrow$ AISC TABLE J.2.4 — OVER 1/2 TO 3/4 MIN = $1/4^{IN}$

MAX SIZE OF WELD $\quad t \geq 5/8^{IN} \quad a = t - 1/16^{IN} \rightarrow a \leq 5/8 - \frac{1}{16} = 9/16^{IN}$

$1/4^{IN} \leq a \leq 9/16^{IN}$

USE $a = 9/16^{IN}$ FILLET WELD

FILLET WELD CAPACITY $\rightarrow t_e = 0.707\left(9/16\right) = 0.398^{IN}$

NOMINAL CAPACITY OF WELD METAL $R_n = F_w t_e = 0.6\,F_{EXX} t_e$

$= 0.6\,(70)(0.398) = 16.70^{K}/IN$

BASE METAL STRENGTH: SHEAR YIELDING; $R_n = 0.6 F_y t$

$= 0.6\,(36)(5/8) = 13.5^{K}/IN$

SHEAR RUPTURE $R_n = 0.6 F_u t$

$= 0.6\,(58)(5/8) = 21.75^{K}/IN$

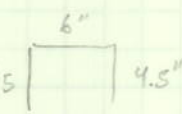
DESIGN STRENGTH $\phi R_n = 0.75(13.5) = 10.125^{K}/IN$

ANGLE LIMIT STATES: YIELD ON GROSS AREA: $\phi F_y A_g = 0.9(36)(5/8'' \cdot 16'') = 324^{K}$

FRACTURE ON NET AREA $\phi F_u A_e = 0.75(58)(5/8'' \cdot 16'') = 435^{K}$

TARGET CAPACITY FOR WELD $V_u = 300.925^{K}$

REQUIRED WELD LENGTH: $L_w = \frac{V_u}{\phi R_n} = \frac{300.925}{2(10.125)} = 14.86^{IN}$ SAY 15 IN



WELD TO T-BEAM GUSSET: TOP CHORD DOUBLE ANGLE ($2L8 \times 6 \times 3/4$)

$\angle$ WT9 x 79 (18.5 IN LENGTH)

WT12 x 114.5

$t_w = 0.81$ > ANGLE THICKNESS $t = 3/4^{IN}$

$\rightarrow$ USE $t = 3/4^{IN}$

E70 ELECTRODES = 70^{KSI}

MIN SIZE OF WELD $\rightarrow$ AISC TABLE J2.4 $\rightarrow$ OVER 1/2 TO $3/4^{IN}$ $\rightarrow$ USE $1/4^{IN}$

MAX SIZE OF WELD $t \geq 3/4^{IN}$ $a \leq t - 1/16^{IN}$ $\longrightarrow a \leq 3/4 - 1/16 = 11/16^{IN}$

$\rightarrow$ USE $a = 11/16^{IN}$ FILLET WELD

FILLET WELD CAPACITY $t_e = 0.707a = 0.707(11/16) = 0.486^{IN}$

NOMINAL CAPACITY OF WELD METAL: $R_n = F_w t_e = 0.6 F_{EXX} t_e = 0.6(70^{KSI})(0.486^{IN}) = 20.41^{K}/_{IN}$

BASE METAL STRENGTH: SHEAR YIELDING. $R_n = 0.6 F_Y A_G = 0.6(36^{KSI})(t = 3/4) = 16^{K}/_{IN}$

SHEAR RUPTURE $R_n = 0.6 F_U A_{NV} = 0.6(58)(3/4) = 26.1^{K}/_{IN}$

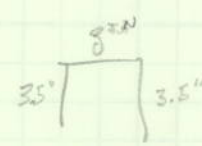
DESIGN STRENGTH = $\phi R_n = 0.75(16.2^{K}/_{IN}) = 12.15^{K}/_{IN}$

ANGLE LIMIT STATES: YIELD ON GROSS AREA: $\phi F_Y A_g = 0.9(36)(3/4 \times 16) = 388.8^{K}$

FRACTURE ON NET AREA: $\phi F_U A_e = 0.75(58)(3/4 \times 16) = 487.2^{K}$

TARGET CAPACITY FOR WELD = $V_U = 354.2^{K}$

REQUIRED WELD LENGTH $L_w = \dfrac{V_U}{\phi R_n} = \dfrac{354.2^{K}}{2(12.15)} = 14.58^{IN}$ SAY 15 IN



Alternative 2

Floor System Beams to Truss Connection

For Nodal Bracing:

Equ (A-6-7) — $P_{br} = 0.02\, M_r C_d / h_o = 0.02\,(1252^k)$

$= 25.04^k$ *Assume $C_d = 1$

Bolts must transfer 25.04^k

- BOLTED THROUGH PLATE AND BOTH FLANGES
- PLATE STEEL: A-36 $F_y = 36$ ksi, $F_u = 58$ ksi
- PLATE SIZE: t_f (truss) $\approx 1.73"$ > 1" > t_f (beam)) ASSUME 1" PLATE
- ASSUME 3/4" BOLTS → A325-N

BOLTS

$A_b = \pi d^2/4 = 0.4418\ in^2$

$\phi R_n = 2\phi F_y A_b = 31.8\ ^k/bolt$ (see Alt 1 connection for details)

$V_u = 66^k$ (trib width = 10')

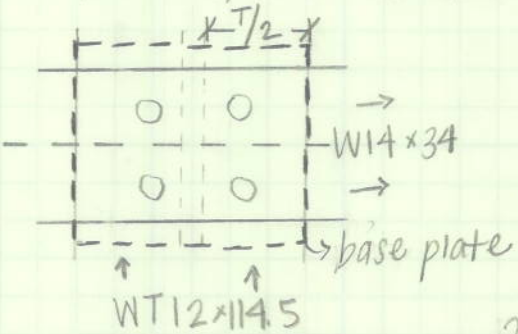
A_w (beam) = 3.99 FOR W14×34

$V_n = 0.6(50)(3.99) = 119.7^k > 66^k$ OK

BOLTS = 66/31.8 = 2.07, use 4 bolts

GEOMETRY

For 3/4" bolts, 1¼" at sheared edges (T.J3.4 AISC Manual)



$T = (b_f = 13.1") - (t_w = 0.93") = 12.17"$

$T/2 = 6.085"$

TOTAL = $2(1\tfrac{1}{4}) = 2.5"$

$2.5" \times 2$ sides $= 5"$

$T/2 = 6.085 \geq L = 5" \leq 12.17"$ NO GOOD USE $L = T/2 = 6.1$

$L_{plate} \geq 6.1" + (t_w = 0.93) = 7.013$

W14×34 $b_f = 6.75"$

WT12×114.5 $b_f = 13.1"$

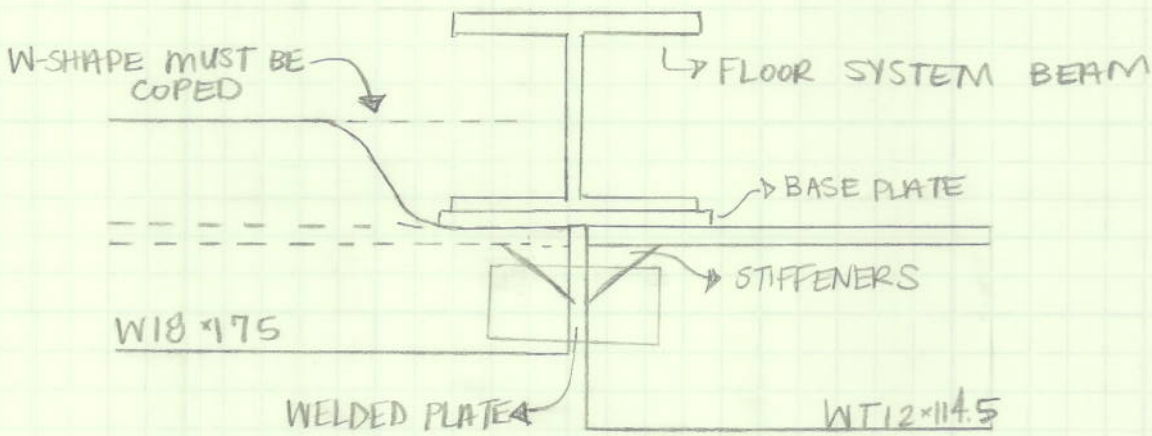
$A_{plate} = b_f$ (truss) $= 13.1"$ (say 13") × b_f (beam) + 2" (1" on each side) = 8.75" say 9"

$A_{plate} = 13" \times 9"$

Alternative 2 - Connections

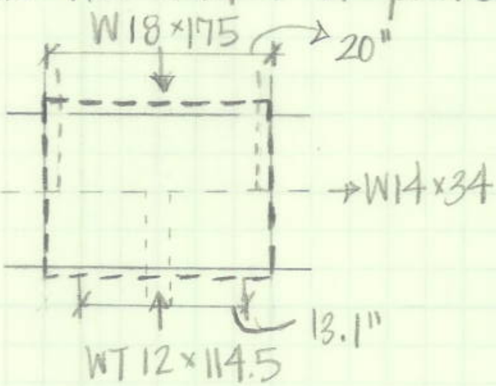
Floor System Beam to Top Chord T-beam/W-shape
(Member B to Rest of Truss)

Member B (I-beam) Rest of Truss (T-beam)



\# BOLTS → same as "FRAME SYSTEM BEAMS TO TRUSS CONNECTION"
USE 4 BOLTS, 3/4" ϕ

GEOMETRY → since we want as little coping as possible, do not add 1" of plate to either side



Since W18×175 is larger (20" vs. 13.1"), use a plate to fit W18×175

$A_{plate} = \text{length}_{(w\text{-}shape)} = 20'' \times b_{f\,(beam)} = 6.75''$ → say 7"

$A_{plate} = 20'' \times 7''$

W18×175 must be coped at least 3.5" to fit base plate on web.

In order to prevent buckling or bending of web/flange, add stiffeners

ALTERNATIVE 3

New Length of trusses. Columns are 110'-7" apart. Floor Beams are spaced 10' o.c. until the outside beams which are 10'-3.5" apart.

Therefore design must use effective width of 10.29' to be conservative.

ENSURE PROPOSED SYSTEM IS ADEQUATE.

GIRDER DESIGN

LL → 100 PSF × 10.29' = 1029 PLF

DL → CONC = 788.5 PLF
DECKING = 29.33 PLF
MEP+CEILING = 154.35 PLF
BEAM (ASSUME W14×34) = 34 PLF

TOTAL DL = 1006.18 PLF

LOAD COMBINATION: $w_u = 1.2D + 1.6L$

$$w_u = 1.2(1006.18) + 1.6(1029) = 2853.82 \text{ PLF} = 2.85 \text{ k/FT}$$

CRITICAL MOMENT

$$M_u = \frac{w_u L^2}{8} = \frac{2.85(24')^2}{8} = 205.47 \text{ k·FT}$$

UNBRACED LENGTH = 24' (MOST TRUSSES SPACED 19'-4" O.C.)

ASSUME a = 2
$Y_{con} = 6"$
$Y_2 = Y_{con} - a/2 = 6" - 2/2 = 5"$
TRY W14×34 → Y_1 @ PNA = 7 (PARTIAL COMPOSITE) = 2.6"
↳ $\phi_b M_n = 297$ k-FT, $A = 10.0 \text{ in}^2$ $d = 14.0"$, $t_w = 0.285"$
(TABLE 3-19) (TABLE 1-1) AISC MANUAL

CHECK CRITICAL MOMENT

LL = 1029 PLF DL = 1006.18 PLF + 34 = 1040.18 PLF

$w_u = 1.2D + 1.6L = 1.2(1040.18) + 1.6(1029) = 2.89 \text{ k/FT}$

$$M_u = \frac{w_u L^2}{8} = \frac{2.89 \text{ k/FT} (24)^2}{8} = 208.41 \text{ k·FT} < 297 \text{ k·FT}$$ OK

TOP + BOTTOM CHORDS

→ MOMENT + BENDING CAPACITY GOVERN

$$M_u = \frac{\frac{(6.6^k/FT)(110.583\ FT)^2}{8}}{h = 7.75'} = 1301.75^{KIPS}$$

- USE SIMILAR SYSTEM TO TRUSS IN GYMNASIUM W/TOP AND BOTTOM CHORDS AS WT SHAPES AND WEB MEMBERS AS DOUBLE ANGLE SHAPES

- USING TABLE 4-7 AND $\phi_c P_n > 1301.75^k$, TRY WT12 x 125, $F_y = 50 ksi$

$$\phi_c P_n = 1390 + \frac{10.29167 - 10}{12 - 10}(1450 - 1390) = 1398.75 \ @ \ b_c = 10'3.5''$$

WEB MEMBERS

DIAGONAL

- MAX AXIAL FORCE IS IN OUTSIDE WEB MEMBER. FROM RISA, MAX AXIAL FORCE = 300.924^k
- USING TABLE 4-9 AND $\phi P_n > 300.924^k$, TRY 2L6 x4 x 3/4

$F_y = 36 ksi$

$$\phi_c P_n = 307 + \frac{8.739 - 8}{10 - 8}(332 - 307) = 316.24^k \ @ \ b_c = 8.739^{FT}$$

- HALF OF THE MEMBERS HAVE AN AXIAL FORCE OF 150.462^k FOR THESE MEMBERS, TRY 2L5 x 3 x 7/16

$F_y = 36 ksi$

$$\phi_c P_n = 159 + \frac{8.739 - 8}{10 - 8}(177 - 159) = 165.651^k \ @ \ b_c = 8.739^{FT}$$

VERTICAL MEMBERS

- MAX AXIAL FORCE IS FOUND TO BE 156.26^k IN OUTSIDE VERTICAL MEMBER
- USING TABLE 4-9, TRY 2L4 x 3 x 5/8

$F_y = 36 ksi$

$\phi_c P_n$ @ EFFECTIVE LENGTH ≈ 8' = 183^k

COMPOSITE CAPACITY

$\Sigma Q_n = 125^k$ (AISC TABLE 3-19) $\qquad f'_c = 4000\,psi = 4\,ksi$

EFFECTIVE WIDTH

$b_E < 1/4\,L = 1/4\,(24') = 72''$

$b_E < s = 72''$

$a = \dfrac{\Sigma Q_n}{0.85 f'_c b_E} = \dfrac{125}{0.85(4)(72)} = 0.511 \qquad Y_2 = 6 - 0.511/2 = 5.74''$

$Y_2 = 5.5'' \qquad \phi_b M_n = 301\,k\text{-}FT$

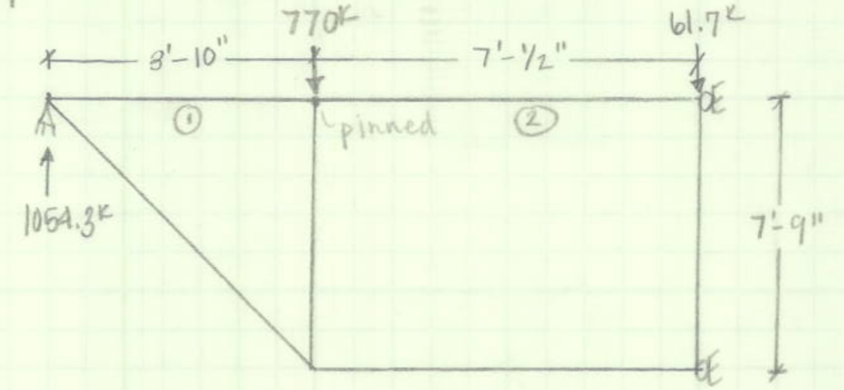
$Y_2 = 5.74'' \qquad \phi_b M_n = 303.4\,k\text{-}FT \qquad \dfrac{5.74 - 5.5}{6.0 - 5.5} = \dfrac{x}{306 - 301} = 2.4 + 301 = 303.4$

$Y_2 = 6.0'' \qquad \phi_b M_n = 306\,k\text{-}FT$

$\phi_b M_n = 303.4\,k\text{-}FT > 208.41\,k\text{-}FT$ <u>OK</u>

Alternative 3

Top chord of Frame on Quad side



RISA ANALYSIS → member ② max moment = 435'k

Using Z_y table T.3.4 (AISC manual), Try W18×192

$\phi_b M_{px} = 446'^k > 435'^k$ <u>OK</u>

RISA ANALYSIS → member ① axial force = 36k

Using T.4.8 (AISC Manual), Try 2L 3×3×7/16

$KL = 3.833'$ $\phi_c P_n = 145^k$ @ 3'

$\phi_c P_n = 136^k$ @ 4'

$\frac{3.833-3}{4-3} = \frac{x}{145-136} = 7.5$ $\phi_c P_n$ @ $3.833' = 137.5^k > 36^k$ <u>OK</u>

Top Chord of Frame on Field side (NO 770k FORCE ACTING ON TOP CHORD)

RISA ANALYSIS → member ② max moment = 386'k

Using T.3.2 (AISC manual) Try W18×175

$\phi_p M_{px} = 398'^k > 386'^k$ <u>OK</u>

RISA ANALYSIS → member ① axial force = 29k

Using T.4.8 (AISC Manual), Try 2L3×3×7/16 KL = 4.25

$\phi_c P_n = 136^k$ @ 4'

$\phi_c P_n = 125^k$ @ 5'

$\frac{4.25-4}{5-4} = \frac{x}{136-125}$ $\phi_c P_n$ @ $4.25' = 133.25^k > 29^k$

<u>OK</u>

FOR FRAME COMPONENT OF TRUSS ON QUAD SIDE:

ADDED 770^k FROM COLUMNS ABOVE, MAX. AXIAL FORCE ON DIAGONAL MEMBER IS 973.241^k

effective length = 8.4'

2L 8×8×1 1/8 → Table 4-8

$$\phi_c P_n = 996^k - \frac{8.4-8}{10-8}(996-950) = 986.8^k > 973.241^k$$

OK

MAX AXIAL FORCE ON VERTICAL MEMBER IS 897.518^k

effective length = 7.75'

W12×79 → Table 4-1

$$\phi_c P_n = 987 - \frac{7.75-7}{8-7}(987-971) = 975^k > 897.518^k$$

OK

ALT 3 COLUMN DESIGN

LIVE LOAD = 100 PSF × 24 FT × 55.29 FT = 132.7 K

DEAD LOAD
CONCRETE = [(145 PCF × 6"/12") − 2.84] × 1.1 × 24 × 55.29 = 101.65 K
MEP + CEILING : 15 PSF × 24 × 55.29 FT = 19.90 K
DECKING = 2.84 PSF × 24 × 55.29 FT = 3.77 K
GIRDER = 34 PLF × 55.29 = 1.88 K
TRUSS = 34.6 K / 2 = 17.3 K

TOTAL DL = 144.5 K

* USING MOST CONSERVATIVE APPROACH
W21x44 HEAVIEST BEAM

ROBOT PIT CEILING
GIRDER 44* PLF × 20 FT 0.88 K
19 PLF × 10 FT = 0.19 K
REFERENCE S109
ASSUME 20 FT LONGEST SPAN
5PSF
CONCRETE = [(145 PCF × 0.625) − 2.84] × 1.1 × 9 FT × 20 FT = 17.58 K
4 inch all across
DECKING = 2.84 × 20 × 9 = 0.511 K
CEILING = 5 PSF × 20 × 9 = 0.9 K → TOTAL DL ROBOT PIT = 19.86 K

EXIT CORRIDORS + PUBLIC SPACES
LIVE LOAD = 100 PSF × 9 FT × 20 FT = 18 K

Check column schedule for loads

LOAD COMBINATION 1.2 D + 1.6 L

$1.2(143.38 + 19.86) + 1.6(132.7 + 18) = 437^K$

look for V=?. notes

GRAVITY SYSTEM, ASSUME KL = 1 $(1.0)(13^{FT}) = 13^{FT}$

EXISTING COLUMNS THAT WILL BE ADEQUATE

F-7.2	W12×65	$\phi_c P_n$ 706 K
F-7.2	W12×53	$\phi_c P_n$ 525 K
G-7.2	W12×53	$\phi_c P_n$ 525 K

REMAINING COLUMNS ARE NOT ADEQUATE (W12×40)

VERIFY AXIAL CAPACITY FOR W12×53 and W12×65

* SEE SPREADSHEET FOR SUPPORTING CALCULATIONS.

USE W12×53 IN PLACE OF W12×40 AT
ALL LOCATIONS OF LINE 7.2.

FOR COLUMNS ON FIELD SIDE (WEST) USE W14 × 90

$V_u = \dfrac{6.6\ ^K/ft \times 110.583\ ft}{2} = 365^K$

P_u (on field side) $= 1.2(143.38) + 1.6(132.7) = 384.376^K$

Alternative 3 - Connections

Floor system Beam to Top Chord T-beam / W-shape

FIELD SIDE

See this connection for Alternative 2

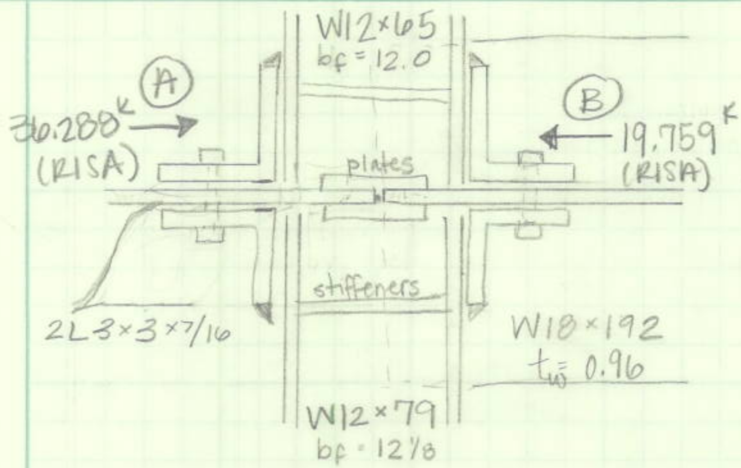
★ Use same detail as Alt. 2 ★

QUAD SIDE

W18×192 vs. W18×175

d = 20.4" d = 20.0"

Since Member B on the Quad side is less than 1/2" larger, the base plate size increase is negligent. ★ Use same detail as Alt. 2 ★



Bearing on web

$$\phi R_{n_{(A)}} = 0.6(1.2)(L_c)(7/16)(58)$$

$$18.27 L_c > V_u$$

$$V_u = 36.28 \;,\; L_c \geq 1.985$$

$$\phi R_{n_{(A)}} = 0.6(2.4)(7/16)(58)(d_B)$$

$$36.54 d_B > V_u$$

$$V_u = 36.28 \;,\; d_B \geq 1$$

DOUBLE SHEAR

Assume 3/4" bolts

$$A_b = \frac{\pi d^2}{4} = \frac{\pi (3/4)^2}{4} = 0.442 \text{ in}^2$$

$$\phi R_n = 2\phi F_y A_b = 2(3/4)(48 \text{ ksi})(0.442) = 31.8 \text{ k/bolts}$$

AISC T.J3.2

Check shear resistance, $\phi V_n = 0.6 F_y A_w$

$A_{w_{(A)}} = (6\frac{3}{8})(7/16) = 2.789$ FOR $2L\,3\times3\times7/16$

$3 + 3 + 3/8$

ALBANO

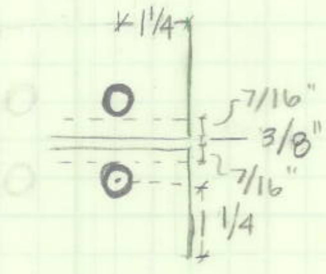
$$\#\text{BOLTS} \rightarrow N = \frac{V_u}{\phi R_n} = \frac{36.3}{31.8} = 1.14 \rightarrow \text{use 2 bolts}$$

max = 36.288^k (RISA)

For 3/4" bolts, min $1\frac{1}{4}$" at sheared edges

AISC T.J3.4

$L = 6.5$



Try L 3×3×3/8

on each side

To prevent buckling

COLUMNS ABOVE EXISTING BENTS

The bents support columns on lines 1 & 7 in Cannon structural drawings.

Line 1 - Field Side - W12×72

Line 7 - Quad Side - W12×65

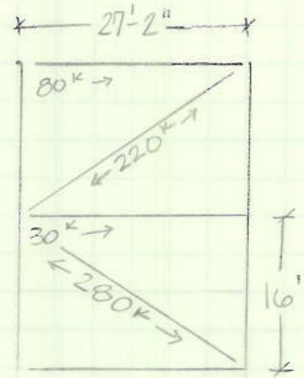
4 S302   5 S302

BRACES 5 S502

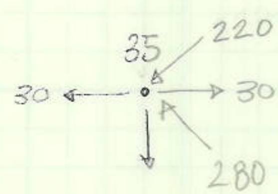
BF 2 LIES ON FIELD SIDE FROM LAST BENT - 24" SPACE - EXISTING WALL

9 S508 - BENT / COLUMN CONNECTION

BF4 LIES ON QUAD SIDE



567'-8"
568'-9" Level 5
552'-9" Level 4



- BRACED FRAME NOTES (S506) W12 → 35k = R for vertical reactions. — use 35 for every connection
- STRUCTURAL NOTE S32, ϕR_n ? ~~WHAT~~ MEAN?
- ALT 3 COLUMNS ON QUAD SIDE ONLY SUPPORT UP UNTIL 4th FLOOR. HOWEVER, WOULD HAVE TO MOVE ABOVE COLUMNS SUPPORTED BY BENTS TO THOSE COLUMNS AS WELL. THAT WOULD EXTEND RUNNING TRACK AND MOVE BRACED FRAMES 4, 5, + 6.

Plate width governed by other beams, use 1st example from 3006 connections

COLUMN DESIGN

Alternative 1

LL	132	k	
DL	159.1	k	
Pu	402.12	k	
Above Forces	770	k	
Updated Pu	1172.12	k	
KL	32.33	ft	K=1.0
Column Size	W14x176		
ϕcPn	1183.33	k	Interpolated from T. 4-1
ry	4.02	in.	
rx	6.432	in.	
Ag	51.8	sq. in.	
E	29000	ksi	
Fy	50	ksi	
KL/ry	96.50746		
λc	113.4318		> KL/ry = 96.5 therefore short & non-slender
Fe	30.73095	ksi	
Fcr	25.30574		
Updated ϕcPn	1179.754	k	> Pu=1172.12 - OK

Use W14x176

COLUMN DESIGN

Alternative 2 (Field Side)

LL	129	k	
DL	140	k	
Pu	374.4	k	
Above Forces	400	k	See spreadsheet
Updated Pu	774.4	k	
KL	32.33	ft	K=1.0
Column Size	W14x132		
ϕcPn	801.33	k	Interpolated from T. 4-1
ry	3.76	in.	
rx	6.28	in.	
Ag	38.8	sq. in.	
E	29000	ksi	
Fy	50	ksi	
KL/ry	103.1808511		
λc	113.4318209		> KL/ry = 96.5 therefore short & non-slender
Fe	26.88434945	ksi	
Fcr	22.9563707		
Updated ϕcPn	801.636465	k	> Pu=774.4 - OK

Use W14x132

COLUMN DESIGN

Alternative 2 (Quad Side)

LL	129	k	
DL	140	k	
Pu	374.4	k	
Above Forces	770	k	
Updated Pu	1144.4	k	
KL	32.33	ft	K=1.0
Column Size	W14x176		
ϕcPn	1183.33	k	Interpolated from T. 4-1
ry	4.02	in.	
rx	6.432	in.	
Ag	51.8	sq. in.	
E	29000	ksi	
Fy	50	ksi	
KL/ry	96.50746		
λc	113.4318		> KL/ry = 96.5 therefore short & non-slender
Fe	30.73095	ksi	
Fcr	25.30574		
Updated ϕcPn	1179.754	k	> Pu=1144.4 - OK

Use W14x176

COLUMN DESIGN

Alternative 3 (Quad Side)

LL	132.7	k	
DL	144.5	k	
Pu	385.72	k	
Above Forces	770	k	See spreadsheet
Updated Pu	1155.72	k	
KL	32.33	ft	K=1.0
Column Size	W14x176		
ϕcPn	1183.33	k	Interpolated from T. 4-1
ry	4.02	in.	
rx	6.432	in.	
Ag	51.8	sq. in.	
E	29000	ksi	
Fy	50	ksi	
KL/ry	96.50746		
λc	113.4318		> KL/ry = 96.5 therefore short & non-slender
Fe	30.73095	ksi	
Fcr	25.30574		
Updated ϕcPn	1179.754	k	> Pu=1155.72 - OK

Use W14x176

COLUMN DESIGN

Alternative 3 (Field Side)

LL	132.7	k	
DL	144.5	k	
Pu	385.72	k	
Above Forces	400	k	See spreadsheet
Updated Pu	785.72	k	
KL	32.33	ft	K=1.0
Column Size	W14x132		
ϕcPn	801.33	k	Interpolated from T. 4-1
ry	3.76	in.	
rx	6.28	in.	
Ag	38.8	sq. in.	
E	29000	ksi	
Fy	50	ksi	
KL/ry	103.1809		
λc	113.4318		> KL/ry = 96.5 therefore short & non-slender
Fe	26.88435	ksi	
Fcr	22.95637		
Updated ϕcPn	801.6365	k	> Pu=785.72 - OK

Use W14x132

Weld Connections - Alternative 2

Top and Bottom Chords to Diagonal Web Member (inside)

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	2L5x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	150.462	k	
Required Weld Length Lw	10.61	in	
Say	11	in	
Angle Limit States:			
Yield on Gross Area	155.925	k	
Fracture on Net Area	209.34	k	
Aisc Table J2.4			
t<1/4	0.125		
1/4<t<1/2	0.188		
1/2<t<3/4	0.25		
t>3/4	0.313		

Vertical Frame Member to Top Chord of Frame

Member 1	2L3x3x7/16		
tw	0.4375	in	
Member 2	2L6x4x5/8		
t	0.625	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	61.697	k	
Required Weld Length Lw	4.35	in	
Say	5	in	
Angle Limit States:			
Yield on Gross Area	70.875	k	
Fracture on Net Area	95.16	k	

Vertical Frame Member to Bottom of Frame

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	2L6x4x5/8		
t	0.625	in	
Use t =	0.625	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.250		
Maximum Size of Weld	0.56	in	
Use a =	0.56	in	Fillet Weld
Fillet Weld Capacity te	0.40	in	
Nominal Capacity of Weld Metal Rn	16.70	k/in	
Base Metal Strength:			
Shear Yielding	13.5	k/in	
Shear Rupture	21.75	k/in	
Design Strength ϕRn	10.125	k/in	
Target Capacity of Weld Vu	61.697	k	
Required Weld Length Lw	3.05	in	
Say	4	in	
Angle Limit States:			
Yield on Gross Area	81	k	
Fracture on Net Area	108.75	k	

Top and Bottom Chords to Diagonal Web Member (outside)

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	2L6x4x5/8		
t	0.625	in	
Use t =	0.625	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.250		
Maximum Size of Weld	0.56	in	
Use a =	0.56	in	Fillet Weld
Fillet Weld Capacity te	0.40	in	
Nominal Capacity of Weld Metal Rn	16.70	k/in	
Base Metal Strength:			
Shear Yielding	13.5	k/in	
Shear Rupture	21.75	k/in	
Design Strength ϕRn	10.125	k/in	
Target Capacity of Weld Vu	300.925	k	
Required Weld Length Lw	14.86	in	
Say	15	in	
Angle Limit States:			
Yield on Gross Area	303.75	k	
Fracture on Net Area	407.81	k	

Top Chord Frame to T-Beam Gusset

Member 1	WT9x79		
tw	0.81	in	
Member 2	2L3x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	35.883	k	
Required Weld Length Lw	2.53	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	42.525	k	
Fracture on Net Area	57.09	k	

Top and Bottom Chords to Vertical Web Member

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	2L6x4x5/8		
t	0.625	in	
Use t =	0.625	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.25		
Maximum Size of Weld	0.56	in	
Use a =	0.56	in	Fillet Weld
Fillet Weld Capacity te	0.40	in	
Nominal Capacity of Weld Metal Rn	16.70	k/in	
Base Metal Strength:			
Shear Yielding	13.5	k/in	
Shear Rupture	21.75	k/in	
Design Strength ϕRn	10.125	k/in	
Target Capacity of Weld Vu	61.7	k	
Required Weld Length Lw	3.05	in	
Say	4	in	
Angle Limit States:			
Yield on Gross Area	81	k	
Fracture on Net Area	108.75	k	

Top Chord Double Angle to W-shape (Frame)

Member 1	W18x175		
tw	0.89	in	
Member 2	2L3x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	35.883	k	
Required Weld Length Lw	2.53	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	42.525	k	
Fracture on Net Area	57.09	k	

Diagonal Frame Member to T-Beam Gusset

Member 1	WT 9x79		
tw	0.81	in	
Member 2	2L6x4x5/8		
t	0.625	in	
Use t =	0.625	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.250		
Maximum Size of Weld	0.56	in	
Use a =	0.56	in	Fillet Weld
Fillet Weld Capacity te	0.40	in	
Nominal Capacity of Weld Metal Rn	16.70	k/in	
Base Metal Strength:			
Shear Yielding	13.5	k/in	
Shear Rupture	21.75	k/in	
Design Strength ϕRn	10.125	k/in	
Target Capacity of Weld Vu	300.925	k	
Required Weld Length Lw	14.86	in	
Say	15	in	
Angle Limit States:			
Yield on Gross Area	303.75	k	
Fracture on Net Area	407.81	k	

Top Chord W-shape (Frame) to WT-Shape (truss)

Member 1	W18x175		
tw	0.89	in	
Member 2	WT12x114.5		
t	0.96	in	
Use t =	0.89	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.313		
Maximum Size of Weld	0.83	in	
Use a =	0.83	in	Fillet Weld
Fillet Weld Capacity te	0.59	in	
Nominal Capacity of Weld Metal Rn	24.57	k/in	
Base Metal Strength:			
Shear Yielding	19.224	k/in	
Shear Rupture	30.972	k/in	
Design Strength ϕRn	14.418	k/in	
Target Capacity of Weld Vu	531	k	
Required Weld Length Lw	18.41	in	
Say	19	in	
Angle Limit States:			
Yield on Gross Area	547.884	k	
Fracture on Net Area	735.59	k	

Diagonal Frame Member to Bottom Chord T-Beam

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	2L6x4x5/8		
t	0.625	in	
Use t =	0.625	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.250		
Maximum Size of Weld	0.56	in	
Use a =	0.56	in	Fillet Weld
Fillet Weld Capacity te	0.40	in	
Nominal Capacity of Weld Metal Rn	16.70	k/in	
Base Metal Strength:			
Shear Yielding	13.5	k/in	
Shear Rupture	21.75	k/in	
Design Strength ϕRn	10.125	k/in	
Target Capacity of Weld Vu	300.925	k	
Required Weld Length Lw	14.86	in	
Say	15	in	
Angle Limit States:			
Yield on Gross Area	303.75	k	
Fracture on Net Area	407.81	k	

Weld Connections - Alternative 3

Top and Bottom Chords to Diagonal Web Member (outside)

Member 1	WT 12x114.5	
tw	0.96	in
Member 2	2L6x4x3/4	
t	0.75	in
Use t =	0.75	in
Fy	36	ksi
Fu	58	ksi
E70 Electrodes	70	ksi
Minimum Size of Weld	0.25	
Maximum Size of Weld	0.69	in
Use a =	0.69	in Fillet Weld
Fillet Weld Capacity te	0.49	in
Nominal Capacity of Weld Metal Rn	20.41	k/in
Base Metal Strength:		
Shear Yielding	16.2	k/in
Shear Rupture	26.1	k/in
Design Strength ϕRn	12.15	k/in
Target Capacity of Weld Vu	300.924	k
Required Weld Length Lw	12.38	in
Say	13	in
Angle Limit States:		
Yield on Gross Area	315.9	k
Fracture on Net Area	424.13	k

Aisc Table J2.4	
t<1/4	0.125
1/4<t<1/2	0.188
1/2<t<3/4	0.25
t>3/4	0.313

Vertical Frame Member to Top Chord of Frame

Member 1	W12x79	
tw	0.47	in
Member 2	2L3x3x7/16	
t	0.4375	in
Use t =	0.4375	in
Fy	36	ksi
Fu	58	ksi
E70 Electrodes	70	ksi
Minimum Size of Weld	0.188	
Maximum Size of Weld	0.38	in
Use a =	0.38	in Fillet Weld
Fillet Weld Capacity te	0.27	in
Nominal Capacity of Weld Metal Rn	11.14	k/in
Base Metal Strength:		
Shear Yielding	9.45	k/in
Shear Rupture	15.225	k/in
Design Strength ϕRn	7.0875	k/in
Target Capacity of Weld Vu	898	k
Required Weld Length Lw	63.35	in
Say	64	in
Angle Limit States:		
Yield on Gross Area	907.2	k
Fracture on Net Area	1218.00	k

Vertical Frame Member to Bottom Chord WT of Frame

Member 1	W12x79	
tw	0.735	in
Member 2	WT 12x114.5	
t	0.96	in
Use t =	0.735	in
Fy	36	ksi
Fu	58	ksi
E70 Electrodes	70	ksi
Minimum Size of Weld	0.313	
Maximum Size of Weld	0.67	in
Use a =	0.67	in
Fillet Weld Capacity te	0.48	in
Nominal Capacity of Weld Metal Rn	19.97	k/in
Base Metal Strength:		
Shear Yielding	15.876	k/in
Shear Rupture	25.578	k/in
Design Strength ϕRn	11.907	k/in
Target Capacity of Weld Vu	898	k
Required Weld Length Lw	37.71	in
Say	38	in
Angle Limit States:		
Yield on Gross Area	904.932	k
Fracture on Net Area	1214.96	k

Column to Double Angle

Member 1	W12x65	
tw	0.605	in
Member 2	L3.5x3.5x1/2	
t	0.5	in
Use t =	0.5	in
Fy	36	ksi
Fu	58	ksi
E70 Electrodes	70	ksi
Minimum Size of Weld	0.188	
Maximum Size of Weld	0.44	in
Use a =	0.44	in Fillet Weld
Fillet Weld Capacity te	0.31	in
Nominal Capacity of Weld Metal Rn	12.99	k/in
Base Metal Strength:		
Shear Yielding	10.8	k/in
Shear Rupture	17.4	k/in
Design Strength ϕRn	8.1	k/in
Target Capacity of Weld Vu	36	k
Required Weld Length Lw	2.22	in
Say	3	in
Angle Limit States:		
Yield on Gross Area	48.6	k
Fracture on Net Area	65.25	k

Top Chord of Frame (Quad Side) to T-Beam Gusset

Member 1	WT 9x79		
tw	0.81	in	
Member 2	2L3x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	36	k	
Required Weld Length Lw	2.54	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	42.525	k	
Fracture on Net Area	57.09	k	

Top Chord Double Angle to Top Chord W (Frame quad side)

Member 1	2L3x3x7/16		
tw	0.4375	in	
Member 2	W 18x192		
t	0.96	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	36.288	k	
Required Weld Length Lw	2.56	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	42.525	k	
Fracture on Net Area	57.09	k	

Vertical W-Shape to Double Angle

Member 1	W12x79		
tw	0.735	in	
Member 2	L3.5x3.5x1/2		
t	0.5	in	
Use t =	0.5	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.44	in	
Use a =	0.44	in	Fillet Weld
Fillet Weld Capacity te	0.31	in	
Nominal Capacity of Weld Metal Rn	12.99	k/in	
Base Metal Strength:			
Shear Yielding	10.8	k/in	
Shear Rupture	17.4	k/in	
Design Strength ϕRn	8.1	k/in	
Target Capacity of Weld Vu	36	k	
Required Weld Length Lw	2.22	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	48.6	k	
Fracture on Net Area	65.25	k	

Vertical W-Shape to Double Angle

Member 1	W12x65		
tw	0.735	in	
Member 2	L3x3x3/8		
t	0.375	in	
Use t =	0.375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.31	in	
Use a =	0.31	in	Fillet Weld
Fillet Weld Capacity te	0.22	in	
Nominal Capacity of Weld Metal Rn	9.28	k/in	
Base Metal Strength:			
Shear Yielding	8.1	k/in	
Shear Rupture	13.05	k/in	
Design Strength ϕRn	6.075	k/in	
Target Capacity of Weld Vu	36	k	
Required Weld Length Lw	2.96	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	36.45	k	
Fracture on Net Area	48.94	k	

Top and Bottom Chords to Diagonal Web Member (inside), Diagonal in Frame (Field Side)

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	2L5x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.000		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	150.462	k	
Required Weld Length Lw	10.61	in	
Say	11	in	
Angle Limit States:			
Yield on Gross Area	155.925	k	
Fracture on Net Area	209.34	k	

Top Chord of Frame (Field Side) to T-Beam Gusset

Member 1	WT 9x79		
tw	0.81	in	
Member 2	2L3x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	29	k	
Required Weld Length Lw	2.05	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	42.525	k	
Fracture on Net Area	57.09	k	

Top Chord W (Frame quad side) to WT shape (truss)

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	W 18x192		
t	0.96	in	
Use t =	0.96	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.313		
Maximum Size of Weld	0.90	in	
Use a =	0.90	in	Fillet Weld
Fillet Weld Capacity te	0.63	in	
Nominal Capacity of Weld Metal Rn	26.65	k/in	
Base Metal Strength:			
Shear Yielding	20.736	k/in	
Shear Rupture	33.408	k/in	
Design Strength ϕRn	15.552	k/in	
Target Capacity of Weld Vu	530.752	k	
Required Weld Length Lw	17.06	in	
Say	18	in	
Angle Limit States:			
Yield on Gross Area	559.872	k	
Fracture on Net Area	751.68	k	

Top and Bottom Chords to Vertical Web Member

Member 1	WT 12x114.5		
tw	0.96	in	
Member 2	2L4x3x5/8		
t	0.625	in	
Use t =	0.625	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.25		
Maximum Size of Weld	0.56	in	
Use a =	0.56	in	Fillet Weld
Fillet Weld Capacity te	0.40	in	
Nominal Capacity of Weld Metal Rn	16.70	k/in	
Base Metal Strength:			
Shear Yielding	13.5	k/in	
Shear Rupture	21.75	k/in	
Design Strength ϕRn	10.125	k/in	
Target Capacity of Weld Vu	62	k	
Required Weld Length Lw	3.06	in	
Say	4	in	
Angle Limit States:			
Yield on Gross Area	81	k	
Fracture on Net Area	108.75	k	

Top chord double angle to top cord w shape (field side)

Member 1	2L4x3x5/8		
tw	0.625	in	
Member 2	2L3x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	62	k	
Required Weld Length Lw	4.37	in	
Say	5	in	
Angle Limit States:			
Yield on Gross Area	70.875	k	
Fracture on Net Area	95.16	k	

Diagonal double angle(Frame field side) to WT shape gusset

Member 1	WT 9x79		
tw	0.81	in	
Member 2	2L5x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	71.849	k	
Required Weld Length Lw	5.07	in	
Say	6	in	
Angle Limit States:			
Yield on Gross Area	85.05	k	
Fracture on Net Area	114.19	k	

Diagonal Frame Member to T-Beam Gusset

Member 1	WT 9x79		
tw	0.81	in	
Member 2	2L8x8x1-1/8		
t	1.125	in	
Use t =	0.81	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.313		
Maximum Size of Weld	0.75	in	
Use a =	0.75	in	Fillet Weld
Fillet Weld Capacity te	0.53	in	
Nominal Capacity of Weld Metal Rn	22.20	k/in	
Base Metal Strength:			
Shear Yielding	17.496	k/in	
Shear Rupture	28.188	k/in	
Design Strength ϕRn	13.122	k/in	
Target Capacity of Weld Vu	973.241	k	
Required Weld Length Lw	37.08	in	
Say	38	in	
Angle Limit States:			
Yield on Gross Area	997.272	k	
Fracture on Net Area	1338.93	k	

Top chord double angle to top cord w shape (field side)

Member 1	W18x175		
tw	0.89	in	
Member 2	2L3x3x7/16		
t	0.4375	in	
Use t =	0.4375	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.188		
Maximum Size of Weld	0.38	in	
Use a =	0.38	in	Fillet Weld
Fillet Weld Capacity te	0.27	in	
Nominal Capacity of Weld Metal Rn	11.14	k/in	
Base Metal Strength:			
Shear Yielding	9.45	k/in	
Shear Rupture	15.225	k/in	
Design Strength ϕRn	7.0875	k/in	
Target Capacity of Weld Vu	28.594	k	
Required Weld Length Lw	2.02	in	
Say	3	in	
Angle Limit States:			
Yield on Gross Area	42.525	k	
Fracture on Net Area	57.09	k	

Diagonal Frame Member to T-Beam Gusset

Member 1	WT12x114.5		
tw	0.96	in	
Member 2	2L8x8x1-1/8		
t	1.125	in	
Use t =	0.96	in	
Fy	36	ksi	
Fu	58	ksi	
E70 Electrodes	70	ksi	
Minimum Size of Weld	0.313		
Maximum Size of Weld	0.90	in	
Use a =	0.90	in	Fillet Weld
Fillet Weld Capacity te	0.63	in	
Nominal Capacity of Weld Metal Rn	26.65	k/in	
Base Metal Strength:			
Shear Yielding	20.736	k/in	
Shear Rupture	33.408	k/in	
Design Strength ϕRn	15.552	k/in	
Target Capacity of Weld Vu	973.241	k	
Required Weld Length Lw	31.29	in	
Say	32	in	
Angle Limit States:			
Yield on Gross Area	995.328	k	
Fracture on Net Area	1336.32	k	

CONNECTION DESIGN
Girder to Column

Alternative 1			
Girder Size	W40x593		
Bolt Diameter	1	in.	
Fy (T. J3.2)	48	k	
A_b	0.785398	sq. in.	
ϕR_n	75.39822	k/bolt	Double Shear
V_u	387.5	k	Found in Alt. 2 Column Design
d (girder)	43	in.	
t_w (girder)	1.79	in.	
A_w	76.97	sq. in.	
ϕV_n	2309.1	k	$\geq V_u$=374.4 k
N = $V_u/\phi R_n$	5.139378	bolts	Use 6 bolts
Actual N (Rounded)	6	bolts	
T (or d-k for T beams)	34	in.	
T/2	17	in.	
Min edge dist. (T. J3.4)	1.75	in.	
Required L	18.5	in.	> T/2 and < T - OK

CONNECTION DESIGN
Top Chord to Column

Alternative 2			
Column Size	W14x176		
Bolt Diameter	1	in.	
Fy (T. J3.2)	48	k	
A_b	0.78539816	sq. in.	
ϕR_n	75.3982237	k/bolt	Double Shear
V_u	308.5	k	Found in RISA Analysis
$N = V_u/\phi R_n$	4.09160833	bolts	Use 6 bolts
Actual N (Rounded)	6	bolts	
N on each side	3	bolts	
Min edge dist. (T. J3.4)	1.75	in.	
Required L	27	in.	From Required Geometry
L_c	1.6875		
1. Bolt Tear Out	131.625	t	
1. Bolt Bearing	156	t	
1. T-beam thickness	0.78125989	in.	GOVERNS
2. T-beam Shear Rupture	1842.75	t	
2. T-beam thickness	0.16741283	in.	
3. T-beam Shear Yield	2106	t	
3. T-beam thickness	0.14648623	in.	
4. T-beam Tear Out	189.54	k	
4. T-beam Bearing	200.448	k	
4. ϕR_n	9097.92	k	> V_u=354.2 k - OK
Required A_w	6.24	sq. in.	
Using gusset WT9x79			
Gusset flange thickness	1.44	in	
Gusset flange A_w	38.88	sq. in.	> A_w=6.24 sq. in.
Gusset web thickness	0.81	in	
Gusset web A_w	21.87	sq. in.	> A_w=6.24 sq. in.
Column flange thickness	1.31	in	
Column flange A_w	35.37	sq. in.	> A_w=6.24 sq. in.

CONNECTION DESIGN
Top Chord to Column

Alternative 3 Quad Side			
Column Size	W14x176		
Bolt Diameter	1	in.	
Fy (T. J3.2)	48	k	
A_b	0.785398	sq. in.	
ϕR_n	75.39822	k/bolt	Double Shear
V_u	1054.3	k	Found in RISA Analysis
$N = V_u/\phi R_n$	13.98309	bolts	Use 6 bolts
Actual N (Rounded)	14	bolts	
N on each side	7	bolts	
Min edge dist. (T. J3.4)	1.75	in.	
Required L	50.3	in.	From Required Geometry
L_c	1.6875		
1. Bolt Tear Out	131.625	t	
1. Bolt Bearing	156	t	
1. T-beam thickness	1.144268	in.	GOVERNS
2. T-beam Shear Rupture	3309.15	t	
2. T-beam thickness	0.318601	in.	
3. T-beam Shear Yield	3923.4	t	
3. T-beam thickness	0.268721	in.	
4. T-beam Tear Out	189.54	k	
4. T-beam Bearing	200.448	k	
4. ϕR_n	9097.92	k	> V_u=354.2 k - OK
Required A_w	6.24	sq. in.	
Using gusset WT12x73			
Gusset flange thickness	1.09	in	
Gusset flange A_w	54.827	sq. in.	> A_w=6.24 sq. in.
Gusset web thickness	0.65	in	
Gusset web A_w	32.695	sq. in.	> A_w=6.24 sq. in.
Column flange thickness	1.31	in	
Column flange A_w	65.893	sq. in.	> A_w=6.24 sq. in.

CONNECTION DESIGN
Top Chord to Column

Alternative 3 Field Side

`	W14x132		
Bolt Diameter	1	in.	
Fy (T. J3.2)	48	k	
A_b	0.785398	sq. in.	
ϕR_n	75.39822	k/bolt	Double Shear
V_u	332	k	Found in RISA Analysis
$N = V_u/\phi R_n$	4.403287	bolts	Use 6 bolts
Actual N (Rounded)	6	bolts	
N on each side	3	bolts	
Min edge dist. (T. J3.4)	1.75	in.	
Required L	27	in.	
L_c	1.6875		
1. Bolt Tear Out	131.625	t	
1. Bolt Bearing	156	t	
1. T-beam thickness	0.840772	in.	GOVERNS
2. T-beam Shear Rupture	1842.75	t	
2. T-beam thickness	0.180166	in.	
3. T-beam Shear Yield	2106	t	
3. T-beam thickness	0.157645	in.	
4. T-beam Tear Out	189.54	k	
4. T-beam Bearing	200.448	k	
4. ϕR_n	9097.92	k	> V_u=354.2 k - OK
Required A_w	6.24	sq. in.	
Using gusset WT9x79, t_w < 0.948			
Gusset flange thickness	1.44	in	
Gusset flange A_w	38.88	sq. in.	> A_w=6.24 sq. in.
Gusset web thickness	0.81	in	
Gusset web A_w	21.87	sq. in.	> A_w=6.24 sq. in.
Column flange thickness	1.03	in	
Column flange A_w	27.81	sq. in.	> A_w=6.24 sq. in.
Using gusset WT9x105.5, t_w > 0.948			
Gusset flange thickness	1.75	in	
Gusset flange A_w	47.25	sq. in.	> A_w=6.24 sq. in.
Gusset web thickness	0.96	in	
Gusset web A_w	25.92	sq. in.	> A_w=6.24 sq. in.
Column flange thickness	1.31	in	
Column flange A_w	35.37	sq. in.	> A_w=6.24 sq. in.

BASE PLATE DESIGN

Alternative 1			
Column Size	W14x176		
d (Column)	15.2	in.	
b_f (Column)	15.7	in.	
f'c (Concrete)	4	ksi	
Fy (plate)	36	ksi	
P_u	1172.12	ksi	
sqrt (A2/A1)	2		
A1	287.2843	sq. in.	
b_f*d	238.64	sq. in.	< A1 therefore use A1
Revised A1	287.2843	in.	
Δ	0.94	in.	
N	17.88946	in.	Say 18
Revised N	18	in.	
B	15.96024	in.	Say 18 to be square
Revised B	18	in.	
Plate Area	324	sq. in.	
ϕcPp	1321.92	k	> Pu = 1172.12 - OK
m	1.78	in.	
n	2.72	in.	
λn'	3.861994	in.	GOVERNS
l	3.86	in.	
t_{req}	1.824078	in.	Say 2 inches

USE PL 1.5 x 16 x 16

BASE PLATE DESIGN

Alternative 2			
Column Size	W14x176		
d (Column)	15.2	in.	
b_f (Column)	15.7	in.	
f'c (Concrete)	4	ksi	
Fy (plate)	36	ksi	
P_u	1144.4	ksi	
sqrt (A2/A1)	2		
A1	280.4902	sq. in.	
b_f*d	238.64	sq. in.	< A1 therefore use A1
Revised A1	280.4902	in.	
Δ	0.94	in.	
N	17.68784	in.	Say 18
Revised N	18	in.	
B	15.58279	in.	Say 18 to be square
Revised B	18	in.	
Plate Area	324	sq. in.	
ϕcPp	1321.92	k	> Pu = 1144.4 - OK
m	1.78	in.	
n	2.72	in.	
λn'	3.861994	in.	GOVERNS
l	3.86	in.	
t_{req}	1.802379	in.	Say 2 inches

BASE PLATE DESIGN

Alternative 3 (Field Side)			
Column Size	W14x132		
d (Column)	14.7	in.	
b_f (Column)	14.7	in.	
f'c (Concrete)	4	ksi	
Fy (plate)	36	ksi	
P_u	784.376	ksi	
sqrt (A2/A1)	2		
A1	192.249	sq. in.	
b_f*d	216.09	sq. in.	> A1 therefore NO GOOD
Revised A1	216.09	in.	
Δ	1.1025	in.	
N	15.8025	in.	Say 16
Revised N	16	in.	
B	13.67442	in.	Say 16 to be square
Revised B	16	in.	
Plate Area	256	sq. in.	
ϕcPp	1044.48	k	> Pu = 402.12 - OK
m	1.0175	in.	
n	2.12	in.	
λn'	3.675	in.	GOVERNS
l	3.675	in.	
t_{req}	1.59824	in.	Say 1.75 inches

BASE PLATE DESIGN

Alternative 3 (Quad Side)			Concrete Pier Must be moved 3'-3" in the South East direction (towards the Quad)
Column Size	W14x176		
d (Column)	15.2	in.	
b_f (Column)	15.7	in.	
f'c (Concrete)	4	ksi	
Fy (plate)	36	ksi	
P_u	1154.376	ksi	
sqrt (A2/A1)	2		
A1	282.9353	sq. in.	
b_f*d	238.64	sq. in.	< A1 therefore use A1
Revised A1	282.9353	in.	
Δ	0.94	in.	
N	17.76068	in.	Say 18
Revised N	18	in.	
B	15.71863	in.	Say 18 to be square
Revised B	18	in.	
Plate Area	324	sq. in.	
ϕcPp	1321.92	k	> Pu = 402.12 - OK
m	1.78	in.	
n	2.72	in.	
λn'	3.861994	in.	GOVERNS
l	3.861994	in.	
t_{req}	1.811154	in.	Say 2 inches

Alternative 2 Weight				
Shape	Weight (plf)	length (ft)	Weight (lb)	
Top Chord				
WT12x114.5	114.5	90	10305	
2L3x3x7/16	16.6	4.8333334	80.23333444	
W18x175	175	12.5	2187.5	
Bottom Chord				
WT12x114.5	114.5	102.5	11736.25	
Vertical Members				
2L6x4x5/8	40	93	3720	
Diagonal Members				
2L5x3x7/16	24	92.23	2213.52	Inside
2L6x4x5/8	40	90.02	3600.8	Outside
Column				
W14x176	176	32.3333	5690.6608	
W14x132	132	32.3333	4267.9956	
T-Beam Gusset				
WT9x79	79	4.5	355.5	

System Weight	44157.45973	lb / truss
9 Trusses	198.7085688	tons

Floor Beams				
W14x34	34	2293.9992	38.9979864	tons

TOTAL	237.7065552	tons
COST @ $2,000/ton	$ 475,413.11	

Alternative 3 Weight				
Shape	Weight (plf)	length (ft)	Weight (lb)	
Top Chord				
WT12x114.5	114.5	90	10305	
2L3x3x7/16	16.6	8.4583	140.40778	
W18x175	175	6.25	1093.75	
W18x192	192	7.04	1351.68	
Bottom Chord				
WT12x114.5	114.5	103.29	11826.705	
Vertical Members				
2L4x3x5/8	27.2	85.25	2318.8	
W12x79	79	7.75	612.25	Quad Frame
Diagonal Members				
2L5x3x7/16	22.6	101.255	2288.363	Inside
2L6x4x3/4	47.2	73.784	3482.6048	Outside
2L8x8x1-1/8	114	8.646	985.644	Quad Frame
Column				
W14x176	176	32.3333	5690.6608	
W14x132	132	32.3333	4267.9956	
T-Beam Gusset				
WT12x73	73	4.1916667	305.9916691	
WT9x79	79	2.25	177.75	

System Weight	44847.60265	lb / truss
9 Trusses	201.8142119	tons

Floor Beams				
W14x34	34	2293.9992	38.9979864	tons

TOTAL	240.8121983	tons
COST @ $2,000/ton	$ 481,624.40	

Alternative 1 Weight				
Shape	Weight (plf)	length (ft)	Weight (lb)	
Girder				
W40x593	593	107.3333	63648.6469	
Column				
W14x176	176	64.666666	11381.33322	
System Weight			75029.98012	lb/truss
9 Girders			337.6349105	tons
Floor Beams				
W14x34	34	2293.9992	38.9979864	tons
TOTAL			376.6328969	tons
COST @ $2,000/ton			$ 753,265.79	

Existing Roof Trusses			
Shape	Weight (plf)	length (ft)	Weight (lb)
Top Chord			
WT10.4x46.5	46.5	107.3333	4991.0
Bottom Chord			
WT10.4x46.5	46.5	104.66667	4867.0
Vertical Members			
2L3.5x3.5x5/16	14.4	53.83335	775.2
2L4x4x3/8	19.6	18	352.8
Diagonal Members			
2L3.5x3.5x5/16	14.4	69.72	1004.0
2L4x4x5/16	16.4	65.44	1073.2
2L4x4x3/8	19.6	33.48	656.2

Sytem Weight	13719.4	lb/truss
25 Trusses	171.492386	tons

*Note that the truss is sloped on the top, so some lengths are estimated

Appendix D – Cost and Schedule Data

Gilbane provided this information:
-Estimated man-hours for erection of the roof trusses = 1280 hours, 8 men for 4 weeks.
-Estimated man-hours for erection of the precast arches = 1920 hours, 8 men for 6 weeks.

Production Rates:
-Roof trusses – 1280 hours for 171.5 tons of steel erected
Erect 0.134 tons or 268 pounds of steel per hour

Man Hours:
Estimate man-hours for erection of our trusses
Alt 1 – 376.6 tons / 0.134 tons/hour = 2810 hours
Alt 3 – 237.7 tons / 0.134 tons/hour = 1774 hours
Alt 3 – 240.8 tons / 0.134 tons/hour = 1797 hours

Material, Labor, Equipment Costs:
-Steel - $2000/ton
Alternative 1 - $753,265.79
Alternative 2 - $475,413.11
Alternative 3 - $481,624.40

Schedule:
Concrete – Started erection Nov. 1st
Duration: 1920 man hours = 6 weeks – 30 days
End Dec. 10th
Alt 2 – Start erection Nov. 1
Duration: 1774 man hours = 5.5 weeks – 27 days
End Dec. 7th

This seems accurate since Neil said it probably would have impacted the schedule a little bit, but not too much. However, 3 extra days means that Gilbane could have poured the topping slab over the floor system before the inclement weather halted production.